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EFFECTS OF INDUCED MOTION CHANGES DURING TASK PERFORMANCE ON PILOT WORKLOAD

by

Alexandria Regina Watson

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN INDUSTRIAL ENGINEERING

Department: Industrial Engineering

Major: Industrial Engineering

Major Professor: Dr. Celestine A. Ntuen

North Carolina A & T State University

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1996

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I give God all the glory for all He has done and will do in my life. Completing my graduate studies has been challenging; however, God has brought me through every trial and tribulation. I thank Him for blessing me with the opportunity to return to my alma marta to work on a masters degree.

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DEDICATION

I dedicate this thesis to God, because all that I have and will get belongs to Him first.

BIOGRAPHICAL SKETCH

Alexandria Regina Watson [redacted] to Walter L. Watson, Jr. and Joice P. Watson. She received the Bachelor of Science in Industrial Engineering from North Carolina Agricultural and Technical State University in 1993. She was also commissioned as a Second Lieutenant in the United States Air Force from Detachment 605 at North Carolina A & T State University in 1993. She is a member of the Human Factors and Ergonomics Society (served as the NC A&T SU Chapter president April 95 - April 96), Institute of Industrial Engineers, Tau Beta Pi Engineering Honor Society, and Alpha Pi Mu Industrial Engineering Honor Society. Alexandria has submitted technical papers for publication in the following: Proceedings for the 19th International Conference on Computers & Industrial Engineering (*Effects of Task Difficulty on Pilot Workload* - March 1996), Proceedings for 1st National Students' Conference Sponsored by the National Alliance of NASA University Research Centers at Minority Institutions (*Effects of Task Difficulty on Pilot Workload and Performance* - February 1996), Proceedings for 3rd Annual Symposium on Human Computer Interaction with Complex Systems (*Workload Prediction as a Function of System Complexity.* - Aug. 1996), and Proceedings for 3rd Annual Symposium on Human Computer Interaction with Complex Systems (*A Fuzzy Model for Workload Assessment in Complex Task Situations* - Aug. 1996). She is a candidate for the Master's in Industrial Engineering.

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ABSTRACT

Watson, Alexandria R. EFFECTS OF MOTION CHANGES DURING TASK PERFORMANCE ON PILOT WORKLOAD. (Major advisor: Dr. Celestine A. Ntuen)

The purpose of this thesis study is to investigate through laboratory experiments, whether motion has any effect on workload during compensatory and pursuit tracking tasks. A workload metric is derived as a function of system complexity. We define system complexity as the ratio of RMS(path) to RMS(velocity or control rate error). Thus, the complexity index allows to quantify workload as a function of error attenuation generated by the operator (path control error) and the task (velocity error). Experiments were conducted at four levels of control dynamics (0th, 1st, 2nd, and 3rd order), three levels of orientation (stationary (no motion), motion with damping coefficient = 0.85 and 2.0). Two tasks, compensatory and pursuit tracking tasks, were performed. The results obtained show that:

(a) Motion does affect error attenuation or the complexity factor and also the workload index.

(b) Pursuit tracking generates more error attenuation and workload than compensatory tracking, especially when they are performed in an unstable (motion-induced) orientation.

(c) The task dynamics or difficulties defined by the control order (position (zero order), velocity (1st order), acceleration (2nd order), and jerk (3rd order)) do have effects on workload.

CHAPTER ONE

Workload Paradigm

1.1 Introduction

In statics, load is defined as the pressure placed upon the surface area of a body. This pressure can be caused by wind, fluids, or the weight of an object. In humans, load refers to the amount pressure placed on the worker (Petersen, 1982). Here, pressure is the work and stress that can stem from both the job and home environment. Therefore, load is the physical, physiological, and psychological effects that result from performing a task.

Load can be classified into two categories: long-term and short-term (Peterson, 1982). Long-term load refers to the stresses due to health (mental and physical) and life situations. For example, if a family member dies or there are marital problems, the worker has long-term stresses that must be dealt with constantly.

On the other hand, short-term load deals with the present work situation. It is dynamic because it may change daily, hourly, and etc. It is a function of the current external influences and internal feelings generated by the task(s) to be carried out in any given work situation. This type of load is termed *workload.* Aspects of workload include physical load, mental load, psychological load, environmental load, and circadian load (Petersen, 1982). Physical load refers to the physical demands placed on the human by a task such as the weight of an object to be lifted, pushed, or pulled. Mental load refers to the capability of the human to perform the information processing requirements of a task. Psychological load refers to the psychological effects of performing a task on the human. For example, some factors that affect psychological load are task-success criteria, feedback, task confusion, and task ambiguity. The environmental load refers to the environment in which the human must perform a task. Examples of factors affecting environmental load are climate, noise levels, and lighting. Circumstance may also affect environmental load such as performing a task in hostile or peaceful surroundings. Circadian load refers to those tasks or environment setting that affect circadian rhythm, for example, working third shift.

1.2 Definition of Operator Workload

In Webster's Dictionary (1976), workload is defined as the amount of work or working time expected from or assigned to an employee. This definition considers an individual operator and implies that the amount of work time and the number of things to be done are pre-defined. However, a scientific definition of workload becomes much more complex than just working time or the amount of the work by an individual. Analysis of the amount of work to be accomplished by an individual can lead to determining the amount of work required by any part of the body such as hands, eyes, brain, etc. For example, a distinction between what aspect of the body is being loaded is made by physical workload and mental workload. Therefore, within the research arena, various definitions of workload exist. The different ways in which workload are viewed make its definition difficult and varied. This leads to three broad categories of workload definitions:

1.2.1 Amount of Work/Number of Things To Do

One definition of operator workload is the absolute amount of work required to complete a task. It quantifies workload in terms of distribution of the amount of work required. Although the amount of work required to complete a task varies with the situation, estimating the distribution of work in any given task situation can be useful. Therefore, this approach defines workload as a function of the task and the situation. Another concept defines workload in a psychomotor context in terms of the number of things to do (Dick, Brown, and Bailey, 1976). Although performance is not well defined, an accuracy or quality component of performance is implied in this definition. Both aspects of this definition of workload are performance-based.

When considering the amount of work or number of things to do as definition of workload, the capacity of the human operator to perform the work must also be taken into account. The term capacity refers to the amount of work the human operator is capable of doing (Grandjean, 1988). Therefore, workload is also dependent on the individual capabilities of the operator and is internal to the operator as well as external. There are three categories of research done in this area.

First, the stable capacity of the operator has been researched to determine the operator's ability to perform a specific task. An example is an operator's ability to lift an object with a given weight amount. Some individuals are physically stronger than others; therefore, their capacity of lifting weight is higher than those who are weaker.

The other two categories of research describe workload as the information processing demands placed on the operator by a task (Sanders and McCormick, 1993). This concept of workload is based on the amount of resources demanded by the task situation and the amount of resources available by the operator to perform in the task situation (McCloy, Derrick, and Wickens, 1983). In other words, workload can be changed by (1) altering the demand of the task on the operator, (2) altering the amount of resource available within the operator, or (3) a combination of both (Sanders and McCormick, 1993).

One of the concepts of workload based on information processing paradigm is the space capacity of an operator available to perform secondary tasks. Research in this area refers to the remaining capacity of the operator performing a primary task, available to perform other tasks (see, e.g. Gopher and Donchin, 1986 and Kantowitz, 1987a). Lysaght, Hill, Dick, et al. (1988) state that the operator is "viewed as having a limited capacity or ability with which to process information." For example a task requiring an operator to use 20% of their capacity leaves 75% of their capacity available for other task performance.

Another workload concept based on information processing is availability of resources. In this context, workload is considered in terms of utilization of specific abilities. These abilities (or resources), such as spatial and verbal, are considered individually and in various combinations (termed multiple resource pools). Here, workload is a function of the task and the resources required to accomplish that task. Furthermore, when more than one task is being performed, workload is dependent on competition of resources. Some studies (see, e.g. Navon and Gopher, 1979) suggest that controls and displays that do not require the same resource pools result in lower levels of workload. Yet other studies (see, e.g. Navon, 1984 and Kantowitz, 1987a) suggest that there is no need to define multiple resource pools of capacity for human information processing.

1.2.2 Working Time

The previous section describes workload in terms of amount of work to be done without consideration to time. Workload can be defined in relation to time. In defining workload in terms of past time, work completed is considered. It involves the effects of fatigue and workload duration on the operator's ability to perform. Little work has been done in the area of defining workload in terms of anticipated or scheduled work (or future time considerations). However, knowledge of past activities can influence current activities (Lysaght, Hill, Dick, et al., 1988, and Sheridan and Simpson, 1979). Time-dependent workload metrics are therefore dynamic.

The most commonly used working time concept involves the present. It considers the time required (Tr) to accomplish the task in relation to the time available (Ta) to finish the task (Holley and Parks, 1987). The ratio of Tr/Ta defines the workload in terms of performance. If the ratio is less than one, the task can be completed in the allotted time. However, the degree of quality of performance is not taken into account. On the other hand, if the ratio is more than one, the task can not be completed in the allotted time period. This means that the operator has more work content in less time. The operator skill and pace may be a factor; but are never considered for workload calculations.

1.2.3 Subjective Psychological Experiences of Human Operator

The previous sections define workload objectively. They omit the operator's perception of task difficulty. To fill this gap, researchers (Hancock and Meshkati, 1988) have defined workload in terms of subjective and psychological variables. Psychological variables involve the efforts necessary for task performance. In this context, workload depends not only on the specific task but also the operator's current capacity to perform the task. Therefore, as the operator's resources are decreased and capabilities limited, the amount of effort expended to perform a task is increased. Workload also depends on the operator's current state. Hence, this workload concept is internal to the operator.

Subjective variables involve the subjective experience of the operator while performing the task. In other words, the operator is "loaded" if he feels loaded regardless of what performance measures show (Johanssen, Moray, Pew, et al., 1979). A three dimensional definition of workload under this concept is based on task complexity, psychological stress, and time constraints (Reid, Shingledecker, and Eggemeir, 1981). Task complexity relates to how the human perceives the degree of the task difficulty in relation to the number of steps required to accomplish the task, the various degrees of freedom, and the task elements. Task complexity may induce psychological stress such as anxiety, frustration, risk, and confusion. Whereas time constraints take into account variables such as number of interruptions and time available to complete the task.

1.3 Operator Workload and Performance

In the definition of operator workload, various affects on performance are mentioned; there is a relationship between performance and workload. This relationship is established by performance factors. According to Lysaght, Dick, Hill, et al. (1988), two major factors affecting performance are the tasks defined by the objectives of the mission (what is to be accomplished) and the environment and the stable and transitory traits of the human operator. Operator performance and system performance are determined by the interaction of these factors. The interaction also determines the operator workload.

The influence the factors affecting performance have on operator workload and performance is discussed by Lysaght, Dick, Hill, et all. (1988). This is shown in Figure 1.

It shows how the two performance factors affect the responses of the operator to the demands of any given task. The top portion contains external factors that combine to create situational demands. The middle portion relates to the operator workload. Approaches to obtaining operator responses are represented in the ovals. Inferences about the operator are made based on the approaches used. All of these elements contribute to the mission performance.

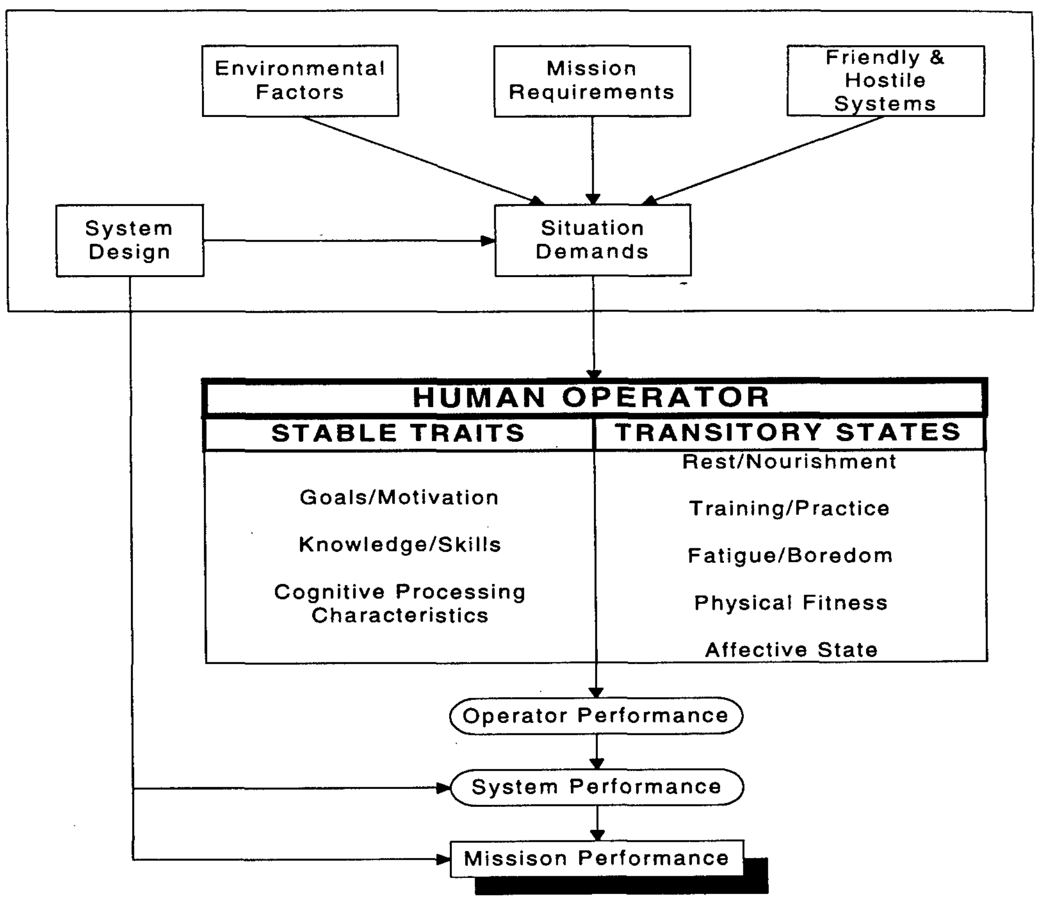

Figure 1. Conceptual Framework of Operator Workload Context and Influences on Operator/System Performance (Lysaght, Dick, Hill, et al., 1988, pp. 11)

1.4 Pilot Workload

Within the aviation community, reduction of workload is a top priority specifically for pilots. During a mission, pilots are bombarded with displays that must be monitored. They are continuously interpreting information and making decisions based on these interpretations. They communicate with other pilots and their crew, air traffic controllers, and etc. Additionally, they may also have to fire or drop weapons on a given target with perfect precision. That they also perform under hostile conditions can add to pilot stress (Wickens, Stokes, Barnett, and Hyman, 1981). Therefore, an effort to create systems that foster acceptable levels of workload in any given situation is imperative to enhancing performance. The relationship between performance and workload as described by Lysaght, Hill, Dick, et al. (1988) is, in short, extremely high or low levels of workload on the human operator results in poor performance. Acceptable performance can be expected at reasonable levels of workload.

Aviation companies are trying to develop and produce aircraft systems that will produce acceptable levels of workload (Hughes, 1989 and Kernstock, 1989). The wave of the future is incorporating automation into the overall design of the cockpit (Hughes, David, and Dornheim, 1995). Quantitative measures of pilot workload and performance are necessary to assist in selecting technologies for full-scale development and integration into new aircraft as well as for the upgrade of current aircraft.

There is no acceptable universal definition of workload; hence, there is not one for pilot workload. However, according to Gawron, Schiflett, and Miller (1989), many definitions contain two common elements. The first is "what the pilot is required to accomplish with the aircraft." The second element is "the conditions or circumstances under which the required operation is to be conducted." This element suggests workload is affected by "the adversiveness of the conditions under which the task(s) are being performed." These conditions include degraded state of the pilot, such as inadequate training or fatigue, and hostile environments, such as extreme temperatures or high gravity. The ability of the pilot to perform tasks is affected by both elements (Harper and Cooper, 1964).

Other studies suggest workload has only one main element. Sarno and Wickens (1992) state that the main contributor to pilot workload is task loading. This is the number of tasks required to be performed at a given instant in time. In system development, the tasks and functions for which the operator will be responsible for are defined. Decisions involving the definition of the tasks and functions are referred to as function allocation (North et al., 1982 and Kantowitz and Sorkin, 1987). According to Beevis (1989), the task load imposed on the operator is defined by the function allocation decisions. These decisions "require verification in terms of the operator's ability to perform the assigned tasks." Workload in this context refers to the load due to the combination of the characteristics of the system and the task demands.

perform the assigned tasks." Workload in this context refers to the load due to the combination of the characteristics of the system and the task demands.

1.5 Compensatory and Pursuit Tracking Task

Tracking tasks are those that require continuous control. It involves executing the correct movements at the correct times. In tracking tasks, the input specifies the desired output which may be constant (e.g., flying a plane at a given altitude) or variable (e.g., tracking a maneuvering aircraft). Typically, the input is directly received from the environment or sensed by mechanical sensors or people. The input signal, referred to as the target, may be presented to operators in the form of signals on a display. Its movement, or course, can be described mathematically or graphically. Although this representation does not depict the real geometry of the input-output relationship in spatial terms, it does characterize the input. Therefore, the input specifies the desired output of the "system," such as curves in a road specify the path a car must follow (McCormick and Sanders, 1982).

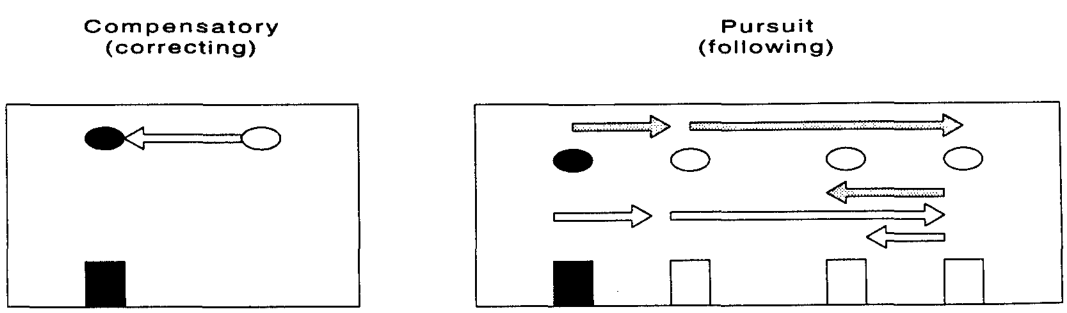

Figure 2. Abstract Displays of Compensatory and Pursuit Tracking Tasks. For compensatory tracking, the black circle represents the controlled element, and the black rectangle represents the fixed target. For pursuit tracking, the black circle represents the moving target, and the black rectangle represents the controlled element. The white arrows represent movement by the operator, and shaded arrows represent movement by the target (Woodson, 1981, pp. 802)

In tracking tasks, the input (target) and output (controlled element) can be presented on a compensatory or pursuit display (see Figure 2). In compensatory tracking, the operator attempts to position the controlled element on a stationary target. The operator is presented the input and output signals in terms of a difference between the system and the operator's control input. This difference is called error, and the operator's function is to minimize or eliminate that error by correctly manipulating the control element (Woodson, 1981). However, in pursuit tracking, the operator attempts to follow the moving target with the control element. The input and output signals are presented with separate indications, each with its own location in space in relation to the other (McCormick and Sanders, 1982).

One of the assumed requirements of the pilot in an automated cockpit environment is that the pilot should have the capability to compensate for the automated system failure. The goal of compensatory tracking model is typically to minimize the time-averaged delays between apparent task execution failures. For the most part, the pilot's perceptual and control strategies are focused primarily on how to compensate for this failure (Levison, 1979).

Many researchers (see e.g. Jex, McDonnel, and Phatak, 1966) have shown the performance of tracking tasks is affected by the system complexity s. A system complexity is defined as a function of system parameters s: k(s = 1) for zero order, k/s for complexity is defined as a function of system parameters s: k(s = 1) for zero order, k/s for first order, k/s^2 for second order and etc. The orders refer to the control relationships between the movement of a control and the output it is intended to control. The movement of the control device directly controls the output in a position-control (zero order) tracking tasks. In velocity control (first order) tracking tasks, the rate at which the output is being changed is the direct effect of the operator's movement. In other words, this is the rate of change of the position of the control. The second order (acceleration) tracking task involves the rate at which there is a change in the rate of movement of the first order. The third order (jerk) tracking task involves the direct control of the rate of change of the acceleration that controls the rate of change of the position of the controlled element.

The consensus based on previous studies show:

(a) The system may or may not be stationary;

(b) Higher harmonics or oscillations are always present (e.g. the movement of the cursor);

(c) The operator responds only to the current state of the system.

The workload study by Levinson (1979) clearly indicates that, in compensatory control tasks, the ratio of the RMS(path) to RMS(v) can be used to define workload. The RMS(path) is the root means square of path error, and RMS(v) is the root means square for control velocity. Whether the nature of the systems stability defined by damping coefficients affect the workload index is another aspect of study yet to be investigated.

This constitutes the premise for this experimental investigation and are the consideration for motion effects.

1.6 Aircraft, Flight Simulator, and Motion

Obviously, pilots are subjected to motion during flight. Studies (Cardullo, 1992 and Caro, 1979) have divided aircraft motion into two categories. Disturbance motion is a result of forces acting on the aircraft that are independent of input controls. It has two subcategories, random continuous or random discrete. Random discrete disturbance refers to atmospheric phenomena such as wind shear and wind gust. "Rough air" is an example of random continuous disturbance. The second category of aircraft motion, maneuver motion, is a direct result of pilot input controls. It is characterized by three factors: changes in the flight path initiated by the pilot, tracking in high gain, closed-loop control task requiring continuous control input from the pilot, and vehicle with low stability requiring continuous control by the pilot.

In aircraft simulation, the utilization purposes of the simulator must be considered (Cardullo, 1992). Flight simulators are extensively used for training pilots. They are also used for research and development and engineering purposes such as cockpit display design and/or development, performance measurements, handling qualities assessment, and workload assessment. However, the fidelity of the simulator depends on the degree to which environment and equipment cues match the actual aircraft environment

(AGARD Advisory Report No. 159). Environmental cues involve duplicating motion and environment of the actual in-flight environment through the simulator environment. Equipment cues involve duplicating the feel and appearance of the operational aircraft.

The effectiveness of flight simulators with motion has been debated. Some studies (Curry, Hoffman and Young, 1976) show that motion platform simulators were beneficial to pilot performance in the aircraft. Other studies (Puig, Harris, and Richard, 1978) show that the effect of motion on performance in a flight simulator is not significant. Although the fidelity of motion simulators is questionable, continuous motion during flight does affect the pilots. It affects the sensory system of the pilot which can lead to difficulty in reading equipment and controlling the aircraft (Young, Green, Elking, and Kelly, 1964). The sensory effects are caused by induced dynamic changes experienced by the pilot (Ntuen, Council, Winchester, and Park, 1994).

1.7 The Problem

Pilots are required to complete many tasks during flight. The emerging of new automation technologies have not only changed the traditional role of the pilot, but designed with the objective of increasing performance while reducing workload. This may not necessarily be the case. For example, cockpit displays induce high cognitive workload (see, e.g. Taylor, 1989 and Tsang and Vidulich, 1989). Additionally, the task and/or environment noise due to motion may induce workload. Such movement causes difficulty in accurately reading equipment and precisely controlling the aircraft. Postural orientation of the pilot also impacts performance. It does so in either a dynamic mode with continuous motion or a static mode with discrete orientation changes (Ntuen, Council, Winchester, and Park, 1994).

In terms of performance, many studies including Council (1995) have concentrated on human error as the main effects of dynamic postural orientation (DPO). However, there is a relationship between performance and workload as described by Lysaght, Hill, Dick et al. (1988). In short, extremely high or low levels of workload on the human operator resulted in poor performance. Acceptable performance can be expected at reasonable levels of workload. There are few studies available on the effects of workload on performance. However, not many studies have been done on the effects of motion of the task environment on workload. This study is designed to investigate this relationship. That is, the effects of motion induced changes in task environment on pilot workload. In particular, most of the workload metrics are subjective and specific to domain tasks. To develop a general workload metric, an objectively defined quantitative metric is important. This is another problem this thesis will address.

1.8 Scope of Thesis

The success of a mission, either in a stressful or non-stressful environment, depends on the interaction between the pilot and the aircraft. Focusing on pilots, their functions involve problem-solving, planning, and decision making. They must be able to perform all tasks required to fly the aircraft while handling changes in mission objectives, weather, threats, and malfunctions. Factors that affect pilot performance under such conditions include personal characteristics such as experiences, capabilities, biases, and skills. This, combined with the mission demands, which include goals, environment, and aircraft design, will determine the workload. The physical and psychological state also contributes to the level of workload. The ability to complete tracking tasks at various levels of workload will be undertaken. These levels will be brought on through motion induced changes of the task environment and various levels of difficulty within the task. Therefore, experimentation will be conducted under the following assumptions:

A. A fixed-based physical motion simulator is used. Known as the Aggie Flight Simulator Platform (AFSP), it is restricted to two degrees of motion of freedom (2 dof). Motion is in the pitch and roll direction. It is located on the campus of North Carolina Agricultural and Technical State University. It is designed and constructed in the Human-Machine Systems Engineering Laboratory.

B. Continuous angular rotation induces the dynamic pilot orientation.

C. The effects of gravity on any induced motion task are not measured nor considered.

1.9 Objectives of Thesis

The following questions are the basis of the experimental design, execution, and analysis carried out in this study. The objective of this thesis is to answer the following:

A. Is there a statistically significant difference in the complexity parameter (as defined later in this thesis) when tracking tasks are performed during induced motion?

B. Is there a statistically significant difference in pilot workload when tracking tasks are performed during induced motion?

C. Is there a statistically significant difference in pilot workload when performing compensatory tracking tasks versus pursuit tracking tasks?

D. Is there a statistically significant difference in pilot workload when performing tracking tasks under zero, first, second, and third order of control modalities?

1.10 Contributions

The major contributions of this thesis shall be:

A. This study provides a new workload theory that takes into account the system (or task) complexity. This theory can be applied to future studies on pilot workload.

B. This study shall provide insight into the effects of environmental dynamicity and tracking task characteristics on pilot workload.

1.11 Organization of Thesis

This thesis will be presented in the following manner:

Chapter 1: Summarizes workload paradigms, literature review, and brief overview of thesis problem, scope, and objectives.

Chapter 2: Presents detailed description of fundamental theory for workload.

Chapter 3: Presents a description of experimental design and test to support objective based questions.

Chapter 4: Presents result discussions from experiments and data analysis.

Chapter 5: Presents the conclusions, recommendations, and suggestions for further research in topic area.

CHAPTER TWO

Fundamental Workload Theory

2.1 Introduction

The classic workload index based on time analysis is usually defined by (Parks and Boucek, 1989)

$$\text{WL(t)} = \frac{R * Time\text{Re}quired}{TimeAvailable} = \frac{Rt}{T} \tag{2.1}$$

where t is the time required to accomplish the task, T is the time available to finish the task, and R is a learning coefficient. From equation (2.1), there is no consideration for the system or task complexity.

In this thesis, we consider workload as a fucntion of the system complexity. Assume, that as the human performs a task there is a loss of human energy to the system environment resulting in the ability to accomplish the desired task. Gheorghe (1979) notes that this energy loss is an exponential decreasing function of the systems complexity. This is defined by

$$\sigma = \begin{cases} (e^{-a})^{0.5}, & \textit{for system without oscillation} \\ \frac{1}{b} e^{-a}, & \textit{otherwise} \end{cases} \tag{2.2}$$

where σ is the coefficient of energy loss, a is the complexity measure, and b is a damping coefficient.

Hypothetically, assume that a system is known with a defined work content c. This may be a function of time available to accomplish a task. As the human operator energy is dissipated, the amount of work accomplished in terms of the energy level is ($c - \sigma$), $c > 0$. Similarly, the system is gaining on energy level defined by the initial work content plus the energy loss by the human operator. That is, $c + \sigma$.

If we consider the impact of system dynamics in Equation (2.2), we can define a normalized workload index by the ratio of work done by the operator (energy expended) to the system energy. This is defined mathematically by:

$$WL = \begin{cases} \dfrac{c - \sqrt{e^{-a}}}{c + e^{-a}}, & \textit{for normal system without oscillation} \\[2ex] \dfrac{c - \frac{1}{b} e^{-a}}{c + e^{-a}}, & \textit{otherwise} \end{cases} \tag{2.3}$$

here, b is the system damping coefficient defined by

$$b = \begin{cases} > 1; & \textit{overdamped system} \\ = 0; & \textit{normal system with no oscillation} \\ = 1; & \textit{critically damped system} \\ < 1; & \textit{underdamped system.} \end{cases}$$

$$0 \le WL \le 1$$

From equation (2.3)

$$c - (e^{-a})^{1/2} \ge 0 \quad \Rightarrow \quad c \ge (e^{-a})^{1/2} \quad \text{(for } b = 0\text{)} \tag{2.4}$$

$$c - (1/b)(e^{-a}) \ge 0 \quad \Rightarrow \quad c \ge (1/b)(e^{-a}) \quad \text{(for } b > 0\text{)} \tag{2.5}$$

The complexity parameter, a, can be defined in various ways. For tracking tasks, Levison (1979) indicates that workload can be defined by the ratio of RMS(path) to RMS(v). Therefore, for this study, the complexity parameter is defined as follows for compensatory and pursuit tracking tasks:

$$a = \frac{RMS(patherror)}{RMS(v)} \tag{2.6}$$

The parameter, a, can be interpreted in terms of signal-to-noise ratio, or error attenuation factor. We shall confine further discussions to the case of c = 1 (i.e., 100% rated workload content as a benchmark).

2.2 Workload Variations Due to Changes in System Complexity

2.2.1 Workload Differential Model

Assume that the system complexity has increased from a_1 to a_2 due to task difficulty or system instability factors such as motion, noise, etc. The change in workload, $\Delta W(a)$, is given by

$$\Delta W(a) = \int_{a_1}^{a_2} WL(a)da \tag{2.7}$$

By substituting Equation 2.3 into Equation 2.7 and simplifying the integration (see Appendix A), we have

$$\Delta W(a) = \begin{cases} (a + \ln(c + e^{-a})) + 2c^{-0.5}(\arctan(\dfrac{e^{-0.5a}}{c^{-0.5}}))|_{a_1}^{a_2}, & for\ b = 0 \\ (a + \ln(c + e^{-a})) + \dfrac{1}{b}\ln(c + e^{-a})|_{a_1}^{a_2}, & for\ b > 1 \end{cases} \tag{2.9}$$

2.2.2 Sample Experiment and Results

Pilot experiments on pursuit tracking were used to validate the workload model. The tasks were done with the Manual Control Laboratory (MCL) software. The pursuit tracking experiments were conducted at three levels of difficulty defined by the task transfer functions: 0th control order or position tracking (k), 1st control order or rate tracking (k/s), and 2nd control order or acceleration tracking (k/s^2). The damping (amplitude) coefficient, b, was set at values of 0, 1, and 2. Figure 3 shows the workload changes in the system with respect to the complexity parameter, a, defined in Equation 2.6. In Figure 4, we plot workload change $\Delta W(a)$ as a function of complexity parameter, a.

For b = 0, the workload slope change is approximately 0.146 at a complexity change factor of 0.5. For b = 1, the slope change is approximately 0.234, and for b = 2, the slope change is approximately 0.756. The workload changes appear to be linear functions of the task complexity. These results correlate to the plot of workload against the complexity parameter from Equation 2.3.

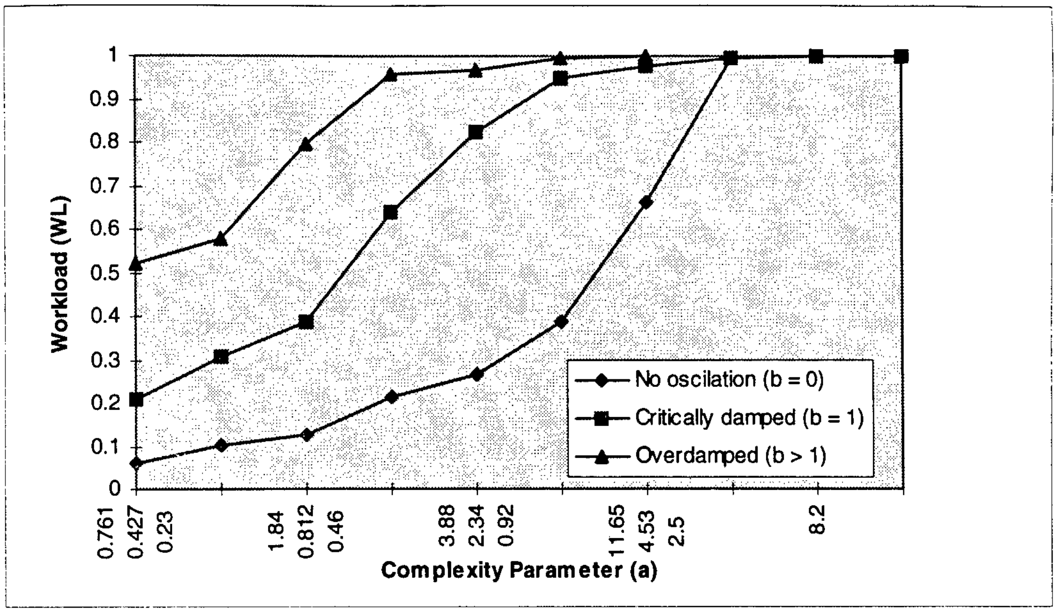

Figure 3. Workload Index as a Function of Changes in System Instability and Complexity

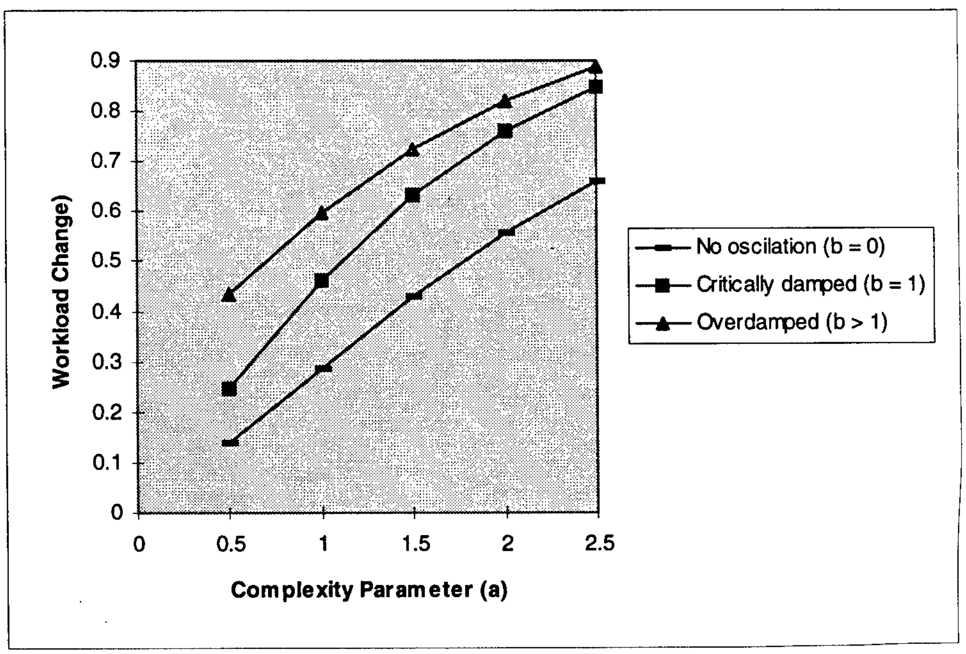

Figure 4. Experimental Workload Index Changes for Different Levels of System Complexity

2.3 Summary

In designing a useful human-machine system, such as an aircraft cockpit, sensitivity analysis of workload changes with system complexity are critical. Current workload models rely heavily on subjective data. Hence, quantifying workload models is difficult. The workload metric derived here is applicable to both subjective and objective data (see, Strickland, Watson, and Ntuen, 1996).

CHAPTER THREE

Experimental Designs and Tests

3.1 Experimental Methodology and Setting

3.1.1 Experimental Goal

The goal of this experiment is to investigate how workload is affected by performing manual control tracking tasks while in motion. Additionally, the effects of tracking task characteristics on task complexity and workload will be investigate.

3.1.2 Subjects

Five subjects (two males and three females), undergraduate and graduate students at North Carolina A & T State University, were selected randomly for this experiment. The subjects range from ages 18 through 30 years old. Subjects participated voluntarily and did not have prior flight experience. Figure 5 shows the equipment setup used with the study.

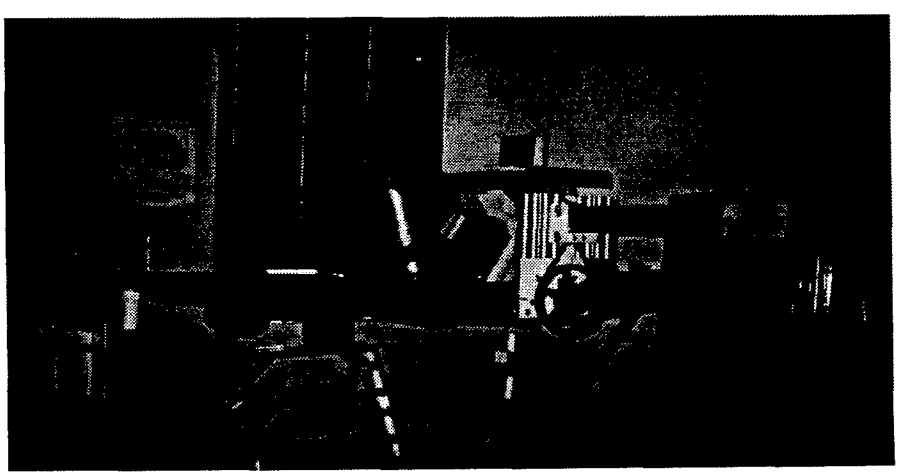

Figure 5. Experimental Setup with AFSP & Laptop Used to Run MCL Software

3.1.3. Equipment

The equipment used in this experiment include a Manual Control Laboratory (MCL) and the Aggie Flight Simulator Platform (AFSP). The MCL uses control tasks to teach and demonstrate manual control concepts. The control tasks demonstrated in this software package include compensatory and pursuit tracking tasks. An IBM compatible computer, color graphics board and monitor, math processor, and mouse were required to run the MCL software.

The MCL provides numerical and graphical feedback on performance. Feedback for all tasks include total time to complete task and sample rate. For compensatory and pursuit tracking tasks, performance feedback include: percent time on target, mean error, root mean square error, standard deviation error, root mean square control error, root mean square control velocity error, bode-amplitude data, and bode-phase data.

Designed for testing subjects in the upright position, the AFSP can move 90° on both the pitch and roll axes. It is a fixed-based physical motion simulator restricted to two degrees of freedom. It is located on the campus of North Carolina Agricultural and Technical State University. It was designed and constructed in the Human-Machine Systems Engineering Laboratory.

3.1.4. Procedure

1. Subjects were acquainted with the experiment.

    - Subjects signed consent forms giving their consent to participate in the experiment (see Appendix B).

    - Subjects were given a description of the compensatory and pursuit tracking tasks.

    - Subjects were given instructions on how to perform the tracking task.

    - Subjects signed consent forms stating they understood the tasks to be performed.

2. All subjects were given five practice trial runs on the MCL for both compensatory and pursuit tracking tasks.

3. Subjects performed tracking tasks in a stationary environment.

4. Once secured on the simulator platform, subjects performed the tasks as instructed while simulator was in motion.

3.2 Experimental Design

3.2.1 Experiment

Four levels of task difficulty on a single-axis (1 degree of freedom) compensatory and pursuit tracking task were presented on a visual display terminal. The display consisted of a vertical line and a target box. In the compensatory tracking tasks, subjects attempted to position the cursor (represented by the vertical line), which was subjected to pseudo-random disturbances, inside a stationary target. In the pursuit tracking tasks, subjects attempted to position the cursor inside a target. Both the cursor and target were subjected to pseudo-random disturbances.

The subjects performed each task set at four levels of difficulty under four different control orders: zero, first, second, and third order. Within the dynamic parameters, the open loop gain, damping factor, stiffness factor, prediction/quicken cursor, position, velocity, and acceleration, and control time delay were fixed for each order (see Table 1). The levels of difficulty were introduced by varying the disturbance over the amplitude of the cursor for compensatory tracking; the target and cursor for pursuit tracking (see Table 2). The disturbance over amplitude values can range from 0.0 to 1.0 half-screen heights. Higher values result in a larger effect of the disturbance. The disturbance parameters remained at the fixed levels provided by the MCL (see Table 2). The degrees of freedom, trial length, number of trials, and target size remained fixed throughout the experiment.

Table 1. Dynamic Parameters for 0th, 1st, 2nd, and 3rd Order Tracking Task

Control Order	0th	1st	2nd	3rd
Open Loop Gain	5.0	5.0	5.0	5.0
Damping Factor	N/A	5.0	5.0	5.0
Stiffness Factor	N/A	N/A	0.65	0.65
Prediction/Quicken (P/Q) On	N/A	N/A	Y	Y
P/Q Cursor	N/A	N/A	1-alone	1-alone
P/Q Position	N/A	N/A	5	5
P/Q Velocity	N/A	N/A	5	5
P/Q Acceleration	N/A	N/A	5	5
Control Time Delay	0.5	0.5	0.5	0.5

Table 2. Levels of Difficulty Determined by Disturbance Overall Amplitude

Level of Difficulty	Disturbance Overall Amplitude Setting
1	0.13
2	0.20
3	0.40
4	1.00

Table 3. Disturbance Parameters for Compensatory and Pursuit Tracking

Disturbance Frequency (radians/second)	Settings
1	0.81955
2	1.39626
3	2.35619
4	1.01054
5	6.98132
6	6.98132
7	6.98132
8	6.98132
9	6.98132
Disturbance Relative Amplitude (range from 0.0 - 1.0)	
1	1.00
2	1.00
3	1.00
4	0.20
5	0.20
6	0.01
7	0.01
8	0.01
9	0.01

Additionally, subjects performed both types of tracking tasks (under the four control orders with the four levels of difficulty) while subjected to three different orientation profiles. The first profile was stationary. Data collected from this profile was used for comparison. The second and third orientation profiles were generated by the AFSP simulation program with damping coefficient values of 0.85 and 2.0, respectively. The experiments involve two types of tracking tasks, three orientations, four control orders, our levels of difficulty, and five trials per level of difficulty. This resulted in 2 x 3 x 4 x 4 fixed effect experiment design. Thus, each subject performed 480 trials. The average experiment lasted for 8 hours per subject.

3.2.2 Design of Experiment

This experiment involves the study of the effects of four factors (subject, orientation, tracking task, control order, and level of difficulty) on pilot workload. A fixed-effect factorial design was used to investigate all possible combinations of the levels of the factors. Each hypothesis was tested using a fixed-effect analysis of variance (ANOVA) model (Montgomery,1991).

All factors in this experiment are fixed; therefore, test hypotheses about the main effects and their interactions were simple. For a fixed effects model, test statistics for each main effect and interaction was constructed by dividing the corresponding mean square for the main effect or interaction by the mean square error. The fixed-effect ANOVA model is defined by:

$$y_{ijklm} = \mu + \tau_i + \beta_j + \gamma_k + \delta_l + \varphi_m + (\beta\gamma)_{jk} + (\beta\delta)_{jl} + (\beta\varphi)_{jm} + (\gamma\delta)_{kl} + (\gamma\varphi)_{km}$$

$$+ (\delta\varphi)_{lm} + (\beta\gamma\delta)_{jkl} + (\beta\gamma\varphi)_{jkm} + (\gamma\delta\varphi)_{klm} + (\beta\delta\varphi)_{jlm} + (\beta\gamma\delta\varphi)_{jklm} + \varepsilon_{jklm} \quad (3.1)$$

where:

i = (1, 2, 3, 4, 5);

where each number represents a subjects

j = (stat, pro1, pro2); for orientation profiles

where:

stat = stationary profile

pro1 = motion profile #1 with b of 0.85

pro2 = motion profile #2 with b of 2.00

k = (comp, purs); for type of tracking task

where:

comp = compensatory tracking task

purs = pursuit tracking task

l = (0, 1, 2, 3); for control order

where:

0 = 0th control order

1 = 1st control order

2 = 2nd control order

3 = 3rd control order

m = (1, 2, 3, 4); for level of difficulty

where:

1 = disturbance amplitude setting of 0.13

2 = disturbance amplitude setting of 0.20

3 = disturbance amplitude setting of 0.40

4 = disturbance amplitude setting of 1.00

τ_i, β_j, γ_k, δ_l, and φ_m are the main effects

$(\beta\gamma)_{jk}$, $(\beta\delta)_{jl}$, $(\beta\varphi)_{jm}$, $(\gamma\delta)_{kl}$, $(\gamma\varphi)_{km}$, and $(\delta\varphi)_{lm}$ are the two-factor interaction effects

$(\beta\gamma\delta)_{jkl}$, $(\beta\gamma\varphi)_{jkm}$, $(\gamma\delta\varphi)_{klm}$, and $(\beta\delta\varphi)_{jlm}$ are the three-factor interaction effects

$(\beta\gamma\delta\varphi)_{jklm}$ is the four-factor interaction effect

For simplification, the effects (or factors) were renamed with the following letters:

A = subjects: i = 1, 2, 3, 4, 5

B = orientation profiles: j = (stationary, motion profile #1, motion profile #2)

C = tracking tasks: k = (compensatory, pursuit)

D = control orders: l = (0, 1, 2, 3 orders)

E = levels of difficulty: m = (1, 2, 3, 4)

BC = interaction between orientation profiles and tracking tasks

BD = interaction between orientation profiles and control orders

BE = interaction between orientation profiles and levels of difficulty

CD = interaction between tracking tasks and control orders

CE = interaction between tracking tasks and levels of difficulty

DE = interaction between control orders and levels of difficulty

BCD = interaction between orientation profiles, tracking tasks, and control order

BCE = interaction between orientation profiles, tracking tasks, and levels of difficulty

BDE = interaction between orientation profiles, control orders, and levels of difficulty

CDE = interaction between tracking tasks, control orders, and levels of difficulty

BCDE = interaction between orientation profiles, tracking tasks, control orders, and levels of difficulty

This model does not include the interaction of factor A (subjects) with any other factors. This was done to block any effect the subjects may have on the data analysis. In this design, all factor levels under a given test scenario were generated and presented randomly. This eliminates the possibility of bias that might occur due to systematic assignment. All ANOVA models were developed and analyzed using SAS™ [1990].

CHAPTER FOUR

Experimental Results and Data Analysis

4.1 Experimental Summary

The experiment designed and discussed in Chapter Three of this thesis was performed with five (5) subjects (3 females and 2 males) selected randomly from the North Carolina A&T student population. The experiment involved five (5) replications (or trials) of manual control tracking tasks (compensatory and pursuit) with four levels of control order at four levels of difficulty. These tasks were performed under three orientation profiles. For the stationary orientation, all subjects performed both types of tracking tasks under all levels of control order with four levels of difficulty (a total of 160 trials per subject). For motion profile #1 ($b = 0.85$), four subjects completed all trials. One subject was unable to complete the experiment. For motion profile #2 ($b = 2.0$), three subjects completed 20 trials and one subject completed 127 trials due to time contraints. Data collected per trial included percent time on target (%Time Tar), mean error (Mean ER), standard error (Sd Er), root mean square of the path error (Rms Stk), and root mean square of the control velocity (Rms Stk Vel) (see Appendix C). The fundamental theory for this thesis only called for the use of the root mean square of the path error and root mean square of the control velocity for data analysis.

4.2 Experimental Results Analysis

The data from the experiment was analyzed by performing an analysis of variance (ANOVA) to test the differences in means of the main effects and interactions. A Tukey test was performed to determine if there was a significant difference in means within the levels of the main effects. The results are as follows:

4.2.1 Analysis of Variance

4.2.1.1 Analysis of Variance with Complexity Parameter as a Workload Measure

We shall use the ANOVA results in Table 5 for discussion in this section.

4.2.1.1.1 Test for Main Effects for Factor A

H_o: There are no differences among the subjects due to variations in complexity parameter.

H_a: At least two of the subjects' means differ.

Test statistic: $$F = \frac{MS(A)}{MSE} \quad (4.1)$$

using data presented in Table 5, we have

$$MS(A) = \frac{SS(A)}{a-1} \quad (4.2)$$

where:

SS(A) = 6.632

a = 5

Table 5. Analysis of Variance Procedure for Complexity Parameter Analysis

Dependent Variable: CP

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	93	34.45027068	0.37043302	6.74	0.0001
Error	1533	84.21497634	0.05493475		
Corrected Total	1626	118.66524702			

R-Square	C.V.	Root MSE	CP Mean
0.290315	55.40615	0.2343816	0.4230246

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SUBJECT	4	6.63243600	1.65810900	30.18	0.0001
ORIENT	2	0.81617481	0.40808740	7.43	0.0006
TASK	1	0.86473763	0.86473763	15.74	0.0001
ORIENT*TASK	2	0.15843461	0.07921730	1.44	0.2368
ORDER	3	15.55686346	5.18562115	94.40	0.0001
ORIENT*ORDER	6	0.90762108	0.15127018	2.75	0.0115
TASK*ORDER	3	3.74861828	1.24953943	22.75	0.0001
ORIENT*TASK*ORDER	5	0.25187365	0.05037473	0.92	0.4689
LEVEL	3	0.28810054	0.09603351	1.75	0.1552
ORIENT*LEVEL	6	0.41882484	0.06980414	1.27	0.2677
TASK*LEVEL	3	0.03838551	0.01279517	0.23	0.8735
ORIENT*TASK*LEVEL	6	0.41380091	0.06896682	1.26	0.2751
ORDER*LEVEL	9	0.67179296	0.07464366	1.36	0.2018
ORIENT*ORDER*LEVEL	18	1.82721934	0.10151219	1.85	0.0163
TASK*ORDER*LEVEL	9	1.56918812	0.17435424	3.17	0.0008
ORIE*TASK*ORDE*LEVEL	13	0.28619893	0.02201530	0.40	0.9700

therefore:

$$MS(A) = \frac{6.632}{4} = 1.658$$

$$MSE = \frac{SSE}{abcde(n-1)} \tag{4.3}$$

where:

SSE = 84.21497634

a = 5, b = 3, c = 2, d = 4, e = 4, n = 5

therefore:

$$MSE = \frac{84.21497634}{1533} = 0.054934752$$

thus, the test statistic, F, can be expressed as:

$$F = \frac{1.658}{0.054934752} = 30.18$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.4}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$F(\nu_1 = (a - 1), \nu_2 = abcde(n-1))$

$F_{\alpha = 0.05, 4, 1533} = 2.37$

since $F = 30.18 > F_{\alpha = 0.05, 4, 1533} = 2.37$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 5 by a p-value (Pr > F) of 0.0001 which is less than $\alpha =$

0.05. Hence, there is evidence of the differences in the way the system complexity affects the subjects in performing tracking tasks.

4.2.1.1.2 Test for Main Effects for Factor B

H_o: There are no differences among the orientation profiles on performance of tracking task.

H_a: At least two of the orientation profiles affect tracking performance.

$$\text{Test statistic:} \qquad F = \frac{MS(B)}{MSE} \tag{4.5}$$

using data presented in Table 5, we have

$$MS(B) = \frac{SS(B)}{b-1} \tag{4.6}$$

where:

$$SS(B) = 0.816$$

$$b = 3$$

therefore:

$$MS(B) = \frac{0.816}{2} = 0.408$$

using Equation 4.6, the test statistic, F, can be expressed as:

$$F = \frac{0.408}{0.054934752} = 7.43$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.7}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 2, 1533} = 3.00$$

since $F = 7.43 > F_{\alpha = 0.05, 2, 1533} = 3.00$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 5 by a p-value (Pr > F) of 0.0006 which is less than α = 0.05. Thus, the orientation profiles affect performance of tracking tasks.

4.2.1.1.3 Test for Main Effects for Factor C

H_o: There is no difference between the effects of compensatory and pursuit tracking tasks on the complexity parameter.

H_a: There is some difference between compensatory and pursuit tracking tasks on the complexity parameter.

Test statistic: $$F = \frac{MS(C)}{MSE} \qquad (4.8)$$

using data presented in Table 5, we have

$$MS(C) = \frac{SS(C)}{c-1} \qquad (4.9)$$

where:

$$SS(C) = 0.865$$

$$c = 2$$

therefore:

$$MS(C) = \frac{0.865}{1} = 0.865$$

using Equation 4.9, the test statistic, F, can be expressed as:

$$F = \frac{0.865}{0.054934752} = 15.74$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.10}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (c - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 1, 1533} = 3.84$$

since $F = 15.74 > F_{\alpha = 0.05, 1, 1533} = 3.84$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 5 by a p-value (Pr > F) of 0.0001 which is less than α = 0.05. Hence, there is evidence of the differences in system complexity for compensatory and pursuit tracking tasks.

4.2.1.1.4 Test for Main Effects for Factor D

H_o: There are no differences among the of control orders.

H_a: At least two of the control order means differ.

Test statistic: $$F = \frac{MS(D)}{MSE} \tag{4.11}$$

using data presented in Table 5, we have

$$MS(D) = \frac{SS(D)}{d-1} \tag{4.12}$$

where:

SS(D) = 15.557

d = 4

therefore:

$$MS(D) = \frac{15.557}{3} = 5.1857$$

using Equation 4.12, the test statistic, F, can be expressed as:

$$F = \frac{5.1857}{0.054934752} = 94.40$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.13}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$F(\nu_1 = (d - 1), \nu_2 = abcde(n-1))$

$F_{\alpha = 0.05, 3, 1533} = 2.60$

since $F = 94.40 > F_{\alpha = 0.05, 3, 1533} = 2.60$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 5 by a p-value (Pr > F) of 0.0001 which is less than α = 0.05. Thus, there is evidence to show the differences in system complexity among control orders.

4.2.1.1.5 Test for Main Effects for Factor E

H_o: There are no differences among the means for the levels of task difficulty.

H_a: There exist some mean differences among the levels of task difficulty.

$$\text{Test statistic:} \qquad F = \frac{MS(E)}{MSE} \tag{4.14}$$

using data presented in Table 5, we have

$$MS(E) = \frac{SS(E)}{e-1} \tag{4.15}$$

where:

SS(E) = 0.288

e = 4

therefore:

$$MS(E) = \frac{0.288}{3} = 0.096$$

using Equation 4.15, the test statistic, F, can be expressed as:

$$F = \frac{0.096}{0.0549347452} = 1.75$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.16}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$F(\nu_1 = (e - 1), \nu_2 = abcde(n-1))$

$$F_{\alpha = 0.05, 3, 1533} = 2.60$$

since $F = 1.75 < F_{\alpha = 0.05, 3, 1533} = 2.60$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 5 by a p-value (Pr > F) of 0.1552 which is more than $\alpha = 0.05$. Thus, the levels of control task difficulty are not significantly different. That is, the control amplitude factor has no noticeable effect on the complexity parameter.

4.2.1.1.6 Test for Factors B and C Interaction

H_o: No interaction between orientation profiles and tracking task type.

H_a: Orientation profiles and tracking task type interact.

Test statistic: $$F = \frac{MS(BC)}{MSE} \tag{4.17}$$

using data presented in Table 5, we have

$$MS(BC) = \frac{SS(BC)}{(b-1)(c-1)} \tag{4.18}$$

where:

$$SS(BC) = 0.158$$

$$(b - 1)(c - 1) = 2$$

therefore:

$$MS(BC) = \frac{0.158}{2} = 0.079$$

using Equation 4.18, the test statistic, F, can be expressed as:

$$F = \frac{0.079}{0.054934752} = 1.44$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.19}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(c - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 2, 1533} = 3.00$$

since $F = 1.44 < F_{\alpha = 0.05, 2, 1533} = 3.00$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 5 by a p-value (Pr > F) of 0.2368 which is less than $\alpha = 0.05$. Hence, there is not sufficient evidence to show that orientation profiles and tracking task types combine to affect the complexity parameter.

4.2.1.1.7 Test for Factors B and D Interaction

H_o: No interaction between orientation profiles and control orders.

H_a: Orientation profiles and control orders interact.

Test statistic: $$F = \frac{MS(BD)}{MSE} \tag{4.20}$$

using data presented in Table 5, we have

$$MS(BD) = \frac{SS(BD)}{(b-1)(d-1)} \tag{4.21}$$

where:

$$SS(BD) = 0.907$$

$$(b - 1)(d - 1) = 6$$

therefore:

$$MS(BD) = \frac{0.907}{6} = 0.1513$$

using Equation 4.21, the test statistic, F, can be expressed as:

$$F = \frac{0.1513}{0.054934752} = 2.75$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.22}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(d - 1),\ \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05,\, 6,\, 1533} = 2.10$$

since $F = 2.75 > F_{\alpha = 0.05,\, 6,\, 1533} = 2.10$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 5 by a p-value (Pr > F) of 0.0115 which is less than α = 0.05. Therefore, orientation profiles and control orders interact as shown in Figure 6. That is, the position for task performance and control order interact to affect the complexity parameter.

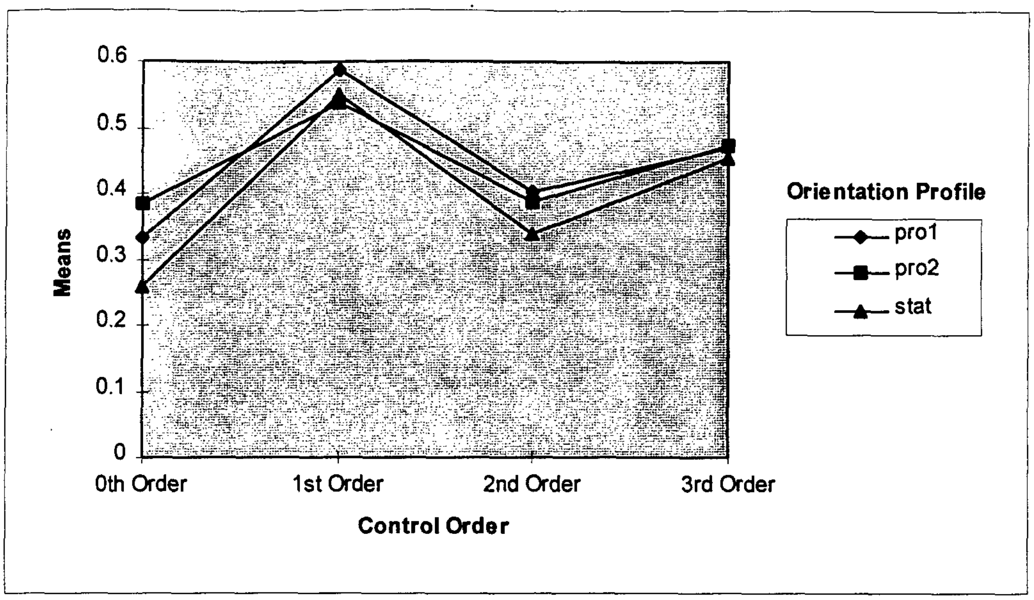

Figure 6. Interaction Between Orientation Profiles and Control Orders

4.2.1.1.8 Test for Factors B and E Interaction

H_o: No interaction between orientation profiles and levels of task difficulty.

H_a: Orientation profiles and levels of task difficulty interact.

$$\text{Test statistic:} \qquad F = \frac{MS(BE)}{MSE} \tag{4.23}$$

using data presented in Table 5, we have

$$MS(BE) = \frac{SS(BE)}{(b-1)(e-1)} \tag{4.24}$$

where:

SS(BE) = 0.419

(b - 1)(e - 1) = 6

therefore:

$$MS(BE) = \frac{0.419}{6} = 0.0698$$

using Equation 4.24, the test statistic, F, can be expressed as:

$$F = \frac{0.0698}{0.054934752} = 1.27$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.25}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(e - 1),\ \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05,\, 6,\, 1533} = 2.10$$

since $F = 1.27 < F_{\alpha = 0.05,\, 6,\, 1533} = 2.10$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 5 by a p-value (Pr > F) of 0.2677 which is more than $\alpha = 0.05$. Hence, there is not sufficient evidence to show that orientation profiles and levels of task difficulty interact. That is, the task position and amplitude do not interact to affect the complexity parameter.

4.2.1.1.9 Test for Factors C and D Interaction

H_o: No interaction between tracking task type and control orders.

H_a: Tracking task type and control orders interact.

Test statistic: $$F = \frac{MS(CD)}{MSE} \tag{4.26}$$

using data presented in Table 5, we have

$$MS(CD) = \frac{SS(CD)}{(c-1)(d-1)} \tag{4.27}$$

where:

SS(CD) = 3.749

(c - 1)(d - 1) = 3

therefore:

$$MS(CD) = \frac{3.749}{3} = 1.2497$$

using Equation 4.27, the test statistic, F, can be expressed as:

$$F = \frac{1.2497}{0.054934752} = 22.75$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha=0.05} \tag{4.28}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$F(\nu_1 = (c - 1)(d - 1), \nu_2 = abcde(n-1))$

$F_{\alpha=0.05, 3, 1533} = 2.60$

since $F = 22.75 > F_{\alpha=0.05, 3, 1533} = 2.60$, there exist sufficient evidence to rejectt H_o. This is significant as shown in Table 5 by a p-value (Pr > F) of 0.0001 which is less than α =

0.05. Thus, there is interaction between tracking task types and control orders as shown in Figure 7.

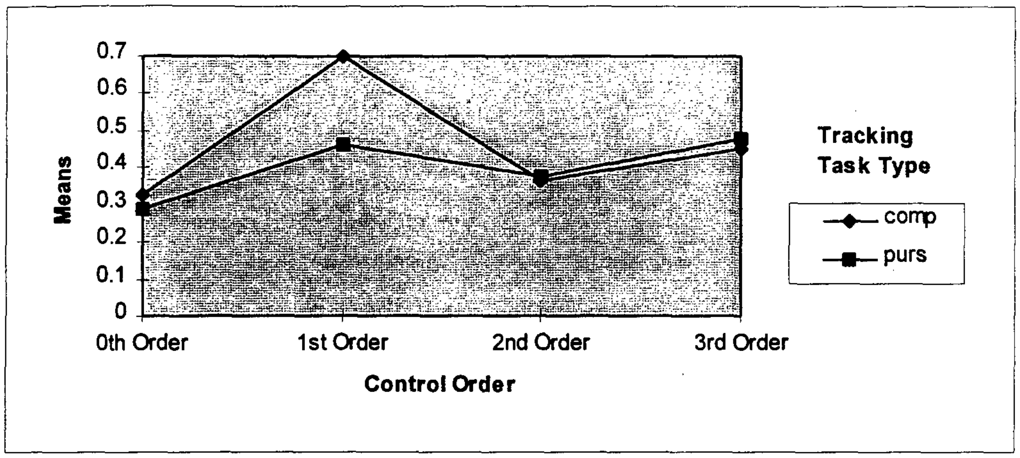

Figure 7. Interaction Between Tracking Task Types and Control Orders

4.2.1.1.10 Test for Factors C and E Interaction

H_o: No interaction between tracking task types and levels of task difficulty.

H_a: Task types and levels of task difficulty interact.

Test statistic: $$F = \frac{MS(CE)}{MSE} \tag{4.29}$$

using data presented in Table 5, we have

$$MS(CD) = \frac{SS(CE)}{(c-1)(e-1)} \tag{4.30}$$

where:

SS(CE) = 0.038

(c - 1)(e - 1) = 3

therefore:

$$MS(CD) = \frac{0.038}{3} = 0.0127$$

using Equation 4.30, the test statistic, F, can be expressed as:

$$F = \frac{0.0127}{0.054934752} = 0.23$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.31}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$F(\nu_1 = (c - 1)(e - 1), \nu_2 = abcde(n-1))$

$F_{\alpha = 0.05, 3, 1533} = 2.60$

since $F = 0.23 < F_{\alpha = 0.05, 3, 1533} = 2.60$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 5 by a p-value (Pr > F) of 0.8735 which is more than $\alpha = 0.05$. Therefore, no evidence exists to show interaction between tracking task types and levels of task difficulty.

4.2.1.1.11 Test for Factors D and E Interaction

H_o: No interaction between control orders and levels of task difficulty.

H_a: Control orders and levels of task difficulty interact.

Test statistic: $$F = \frac{MS(DE)}{MSE} \tag{4.32}$$

using data presented in Table 5, we have

$$MS(DE) = \frac{SS(DE)}{(d-1)(e-1)} \tag{4.33}$$

where:

SS(DE) = 0.672

(d - 1)(e - 1) = 9

therefore:

$$MS(DE) = \frac{0.672}{9} = 0.0747$$

using Equation 4.33, the test statistic, F, can be expressed as:

$$F = \frac{0.0747}{0.054934752} = 1.36$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.34}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (d - 1)(e - 1),\ \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 9, 1533} = 1.88$$

since $F = 1.36 > F_{\alpha = 0.05, 9, 1533} = 1.88$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 5 by a p-value (Pr > F) of 0.2018 which is more than $\alpha = 0.05$. Hence, there is no interaction between control orders and levels of task difficulty.

4.2.1.1.12 Test for Factors B, C, and D Interaction

H_o: No interaction between orientation profiles, tracking task types, and control orders.

H_a: Orientation profiles, tracking task types, and control orders interact.

$$\text{Test statistic:} \qquad F = \frac{MS(BCD)}{MSE} \tag{4.35}$$

using data presented in Table 5, we have

$$MS(BCD) = \frac{SS(BCD)}{(b-1)(c-1)(d-1)} \tag{4.36}$$

where:

SS(BCD) = 0.252

(b - 1)(c - 1)(d - 1) = 5

therefore:

$$MS(BCD) = \frac{0.252}{5} = 0.0504$$

using Equation 4.36, the test statistic, F, can be expressed as:

$$F = \frac{0.0504}{0.054934752} = 0.92$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.37}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(c - 1)(d - 1),\ \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05,\, 5,\, 1533} = 2.21$$

since $F = 0.92 < F_{\alpha = 0.05, 5, 1533} = 2.21$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 5 by a p-value (Pr > F) of 0.4689 which is more than $\alpha = 0.05$. Thus, orientation profiles, tracking task types, and control orders do not interact.

4.2.1.1.13 Test for Factors B, C, and E Interaction

H_o: No interaction between orientation profiles, tracking task types, and levels of difficulty.

H_a: Orientation profiles, tracking task types, and levels of difficulty interact.

Test statistic: $$F = \frac{MS(BCE)}{MSE} \tag{4.38}$$

using data presented in Table 5, we have

$$MS(BCD) = \frac{SS(BCE)}{(b-1)(c-1)(e-1)} \tag{4.39}$$

where:

$$SS(BCE) = 0.414$$

$$(b - 1)(c - 1)(e - 1) = 6$$

therefore:

$$MS(BCD) = \frac{0.414}{6} = 0.069$$

using Equation 4.38, the test statistic, F, can be expressed as:

$$F = \frac{0.069}{0.054934752} = 1.26$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.40}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(c - 1)(e - 1),\ \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 6, 1533} = 2.10$$

since $F = 1.26 < F_{\alpha = 0.05, 6, 1533} = 2.10$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 5 by a p-value (Pr > F) of 0.2751 which is more than $\alpha = 0.05$. Therefore, orientation profiles, tracking task types, and levels of task difficulty do not interact.

4.2.1.1.14 Test for Factors B, D, and E Interaction

H_o: No interaction between orientation profiles, control orders, and levels of task difficulty.

H_a: Orientation profiles, control orders, and levels of task difficulty interact.

Test statistic: $$F = \frac{MS(BDE)}{MSE} \tag{4.41}$$

using data presented in Table 5, we have

$$MS(BDE) = \frac{SS(BDE)}{(b-1)(d-1)(e-1)} \tag{4.42}$$

where:

$$SS(BDE) = 1.827$$

$$(b - 1)(d - 1)(e - 1) = 18$$

therefore:

$$MS(BDE) = \frac{1.827}{18} = 0.1015$$

using Equation 4.41, the test statistic, F, can be expressed as:

$$F = \frac{0.1015}{0.054943752} = 1.85$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.43}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(d - 1)(e - 1),\ \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05,\ 18,\ 1533} = 1.57$$

since $F = 1.85 > F_{\alpha = 0.05,\ 18,\ 1533} = 1.57$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 5 by a p-value (Pr > F) of 0.0163 which is less than α = 0.05. Hence, there is evidence to show that orientation profiles, control orders, and levels of task difficulty interact as shown in Figure 8.

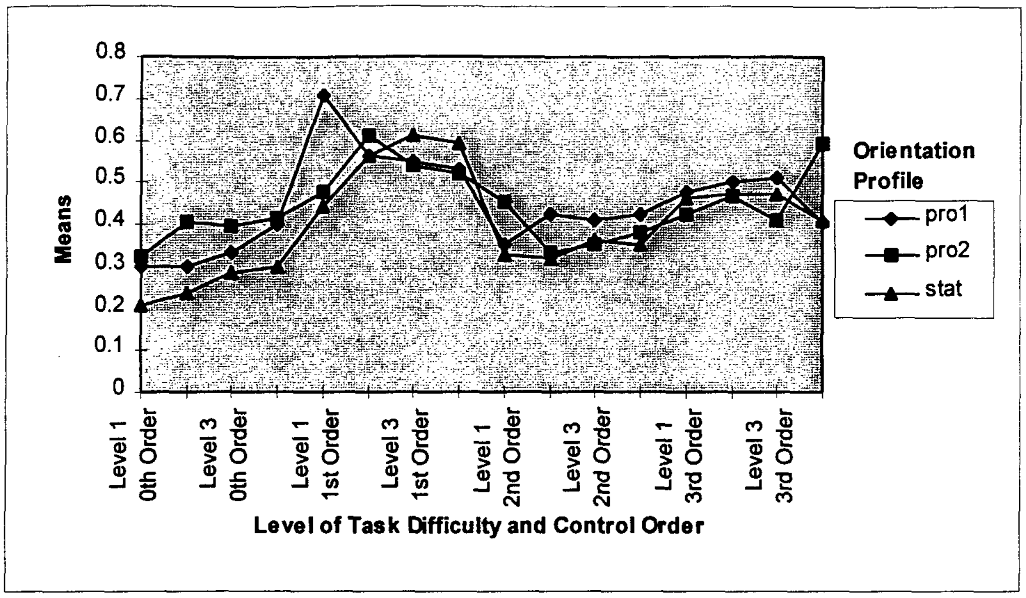

Figure 8. Interaction Between Orientation Profiles, Control Orders and Levels of Task Difficulty

4.2.1.1.15 Test for Factors C, D, and E Interaction

H_o: No interaction between tracking task types, control orders, and levels of task difficulty.

H_a: Tracking task type, control orders, and levels of task difficulty interact.

$$\text{Test statistic:} \qquad F = \frac{MS(CDE)}{MSE} \tag{4.44}$$

using data presented in Table 5, we have

$$MS(CDE) = \frac{SS(CDE)}{(c-1)(d-1)(e-1)} \tag{4.45}$$

where:

SS(CDE) = 1.569

(c - 1)(d - 1)(e - 1) = 9

therefore:

$$MS(CDE) = \frac{1.569}{9} = 0.1743$$

using Equation 4.44, the test statistic, F, can be expressed as:

$$F = \frac{0.1743}{0.054934752} = 3.17$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.46}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (c - 1)(d - 1)(e - 1),\ \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 9, 1533} = 1.88$$

since $F = 3.17 > F_{\alpha = 0.05, 9, 1533} = 1.88$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 5 by a p-value (Pr > F) of 0.0008 which is less than α = 0.05. Therefore, evidence exists to show that tracking task types, control orders, and levels of task difficulty interact as shown in Figure 9.

4.2.1.1.16 Test for Factors B, C, D, and E Interaction

H_o: No interaction between orientation profiles, tracking task types, control orders, and levels of task difficulty.

H_a: Orientation profiles, tracking task types, control orders, and levels of task difficulty interact.

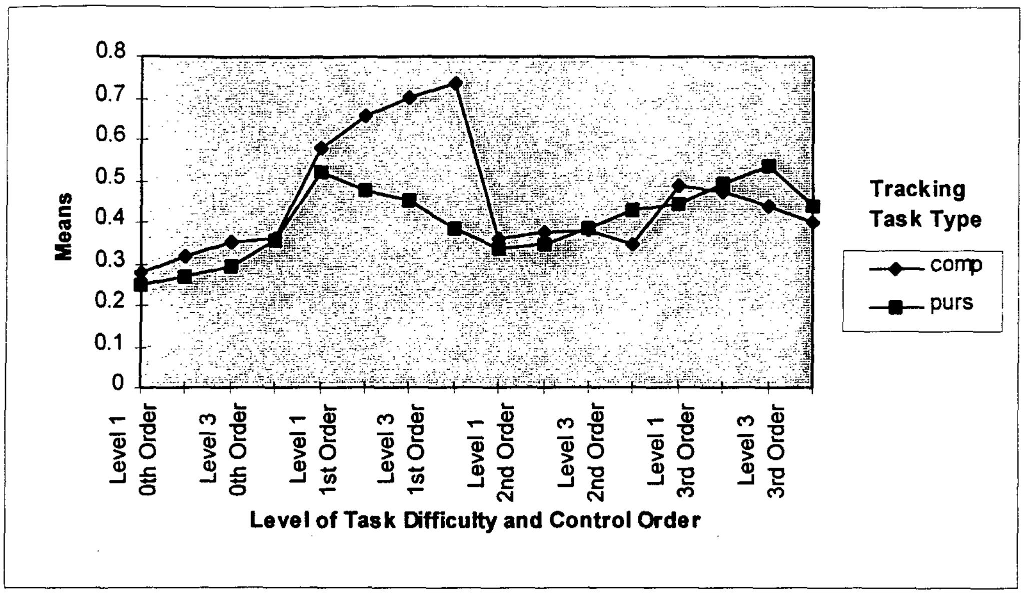

Figure 9. Interaction Between Tracking Task Types, Control Orders, and Levels of Task Difficulty

Test statistic: $$F = \frac{MS(BCDE)}{MSE} \tag{4.47}$$

using data presented in Table 5, we have

$$MS(BCD) = \frac{SS(BCDE)}{(b-1)(c-1)(d-1)(e-1)} \tag{4.48}$$

where:

SS(BCDE) = 0.286

(b - 1)(c - 1)(d - 1)(e - 1) = 13

therefore:

$$MS(BCDE) = \frac{0.286}{13} = 0.022$$

using Equation 4.47, the test statistic, F, can be expressed as:

$$F = \frac{0.022}{0.054934752} = 0.40$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.49}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(c - 1)(d - 1)(e - 1),\ \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05,\ 13,\ 1533} = 1.75$$

since $F = 0.40 < F_{\alpha = 0.05,\ 13,\ 1533} = 1.75$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 5 by a p-value (Pr > F) of 0.9700 which is more than $\alpha = 0.05$. Hence, there is not evidence to show interaction between orientation profiles, tracking task types, control orders, and levels of task difficulty.

4.2.1.2 Analysis of Variance Using Workload Index

4.2.1.2.1 Test for Main Effects for Factor A

H_o: There are no differences among the subjects due to variation in workload.

H_a: At least two of the subject means differ.

Test statistic: $$F = \frac{MS(A)}{MSE} \tag{4.50}$$

using data presented in Table 6, we have

Table 6. Analysis of Variance Procedure for Workload Index Analysis

Dependent Variable: WL

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	93	19.56021918	0.21032494	38.44	0.0001
Error	1533	8.38774049	0.00547145		
Corrected Total	1626	27.94795968			

R-Square	C.V.	Root MSE	WL Mean
0.699880	46.42197	0.0739693	0.1593411

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SUBJECT	4	2.76779881	0.69194970	126.47	0.0001
ORIENT	2	13.19910830	6.59955415	1206.18	0.0001
TASK	1	0.68976843	0.68976843	126.07	0.0001
ORIENT*TASK	2	0.00000000	0.00000000	0.00	1.0000
ORDER	3	1.34160276	0.44720092	81.73	0.0001
ORIENT*ORDER	6	0.83223332	0.13870555	25.35	0.0001
TASK*ORDER	3	0.35574963	0.11858321	21.67	0.0001
ORIENT*TASK*ORDER	5	0.24741628	0.04948326	9.04	0.0001
LEVEL	3	0.01637495	0.00545832	1.00	0.3930
ORIENT*LEVEL	6	0.05449414	0.00908236	1.66	0.1272
TASK*LEVEL	3	0.01307436	0.00435812	0.80	0.4958
ORIENT*TASK*LEVEL	6	0.03834841	0.00639140	1.17	0.3207
ORDER*LEVEL	9	0.09851295	0.01094588	2.00	0.0359
ORIENT*ORDER*LEVEL	18	0.25239441	0.01402191	2.56	0.0003
TASK*ORDER*LEVEL	9	0.18237945	0.02026438	3.70	0.0001
ORIE*TASK*ORDE*LEVEL	13	0.08755502	0.00673500	1.23	0.2504

$$MS(A) = \frac{SS(A)}{a-1} \tag{4.51}$$

where:

SS(A) = 2.7678

a = 5

therefore:

$$MS(A) = \frac{2.7678}{4} = 0.692$$

$$MSE = \frac{SSE}{abcde(n-1)} \tag{4.52}$$

where:

SSE = 8.38774049

a = 5, b = 3, c = 2, d = 4, e = 4, n = 5

therefore:

$$MSE = \frac{8.38774049}{1533} = 0.005471454$$

thus, the test statistic, F, can be expressed as:

$$F = \frac{0.692}{0.005471454} = 126.47$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.53}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (a - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 4, 1533} = 2.37$$

since $F = 126.47 > F_{\alpha = 0.05, 4, 1533} = 2.37$, there exist sufficient evidence to reject H_o. This is significan as shown in Table 6 by a p-value ($Pr > F$) of 0.0001 which is less than α = 0.05. Hence, there is evidence of the differences in subject workload in performing tracking tasks.

4.2.1.2.2 Test for Main Effects for Factor B

H_o: There are no differences among the orientation profiles on workload induced by performance of tracking tasks.

H_a: At least two of the orientation profile means affect workload.

Test statistic: $$F = \frac{MS(B)}{MSE} \tag{4.54}$$

using data presented in Table 6, we have

$$MS(B) = \frac{SS(B)}{b-1} \tag{4.55}$$

where:

$SS(B) = 13.199$

$b = 3$

therefore:

$$MS(B) = \frac{13.199}{2} = 6.5995$$

using Equation 4.54, the test statistic, F, can be expressed as:

$$F = \frac{6.5995}{0.005471454}1206.18$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.56}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 2, 1533} = 3.00$$

since $F = 1206.18 > F_{\alpha = 0.05, 2, 1533} = 3.00$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 6 by a p-value (Pr > F) of 0.0001 which is less than α = 0.05. Thus, orientation profiles affect workload when performing tracking task.

4.2.1.2.3 Test for Main Effects for Factor C

H_o: There is no difference between workload induced by compensatory and pursuit tracking task.

H_a: There is some difference between compensatory and pursuit tracking tasks.

Test statistic: $$F = \frac{MS(C)}{MSE} \tag{4.57}$$

using data presented in Table 6, we have

$$MS(C) = \frac{SS(C)}{c-1} \tag{4.58}$$

where:

$$SS(C) = 0.6897$$

$$c = 2$$

therefore:

$$MS(C) = \frac{0.6897}{1} = 0.6897$$

using Equation 4.57, the test statistic, F, can be expressed as:

$$F = \frac{0.6897}{0.005471454} = 126.07$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.59}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (c - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 1, 1533} = 3.84$$

since $F = 126.07 > F_{\alpha = 0.05, 1, 1533} = 3.84$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 6 by a p-value (Pr > F) of 0.0001 which is less than α = 0.05. Hence, there is evidence of the differences in workload for compensatory and pursuit tracking tasks.

4.2.1.2.4 Test for Main Effects for Factor D

H_o: There are no differences in workload experienced by subjects in different control orders.

H_a: At least two of the control order means differ.

Test statistic: $$F = \frac{MS(D)}{MSE} \quad (4.60)$$

using data presented in Table 6, we have

$$MS(D) = \frac{SS(D)}{d-1} \quad (4.61)$$

where:

SS(D) = 1.3416

d = 4

therefore:

$$MS(D) = \frac{1.3416}{3} = 0.4472$$

using Equation 4.60, the test statistic, F, can be expressed as:

$$F = \frac{0.4472}{0.005471454} = 81.73$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \quad (4.62)$$

where:

F has v_1 and v_2 degrees of freedom respectively, that is:

$F(v_1 = (d - 1), v_2 = abcde(n-1))$

$$F_{\alpha = 0.05, 3, 1533} = 2.60$$

since F = 81.73 > $F_{\alpha = 0.05, 3, 1533}$ = 2.60, there exist sufficient evidence to reject H_o. This is significan as shown in Table 6 by a p-value (Pr > F) of 0.0001 which is less than α = 0.05. Thus, there is evidence to show the the order of control elements affects workload.

4.2.1.2.5 Test for Main Effects for Factor E

H_o: There are no differences in workload as induced by the levels of task difficulty.

H_a: There exists some mean difference among the levels of task difficulty.

Test statistic: $$F = \frac{MS(E)}{MSE} \tag{4.63}$$

using data presented in Table 6, we have

$$MS(E) = \frac{SS(E)}{e-1} \tag{4.64}$$

where:

SS(E) = 0.0164

e = 4

therefore:

$$MS(E) = \frac{0.0164}{3} = 0.00546$$

using Equation 4.63, the test statistic, F, can be expressed as:

$$F = \frac{0.00546}{0.005471454} = 1.00$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.65}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$F(\nu_1 = (e - 1), \nu_2 = abcde(n-1))$

$F_{\alpha = 0.05, 3, 1533} = 2.60$

since $F = 1.00 < F_{\alpha = 0.05, 3, 1533} = 2.60$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 6 by a p-value (Pr > F) of 0.3930 which is more than $\alpha = 0.05$. Thus, the levels of control task difficulty does not affect workload.

4.2.1.2.6 Test for Factors B and C Interaction

H_o: No interaction between orientation profiles and tracking task types in inducing workload.

H_a: Orientation profiles and tracking task types interact to induce workload.

Test statistic: $$F = \frac{MS(BC)}{MSE} \tag{4.66}$$

using data presented in Table 6, we have

$$MS(BC) = \frac{SS(BC)}{(b-1)(c-1)} \tag{4.67}$$

where:

$SS(BC) = 0$

$(b - 1)(c - 1) = 2$

therefore:

$$MS(BC) = \frac{0}{2} = 0$$

using Equation 4.66, the test statistic, F, can be expressed as:

$$F = \frac{0}{0.005471454} = 0$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.68}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(c - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 2, 1533} = 3.00$$

since $F = 0 < F_{\alpha = 0.05, 2, 1533} = 3.00$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 6 by a p-value (Pr > F) of 1.0000 which is less than α = 0.05. Hence, there is not sufficient evidence to show that orientation profiles and tracking task types interact.

4.2.1.2.7 Test for Factors B and D Interaction

H_o: No interaction between orientation profiles and control orders in workload.

H_a: Orientation profiles and control orders interact to induce workload.

Test statistic: $$F = \frac{MS(BD)}{MSE} \tag{4.69}$$

using data presented in Table 6, we have

$$MS(BD) = \frac{SS(BD)}{(b-1)(d-1)} \tag{4.70}$$

where:

$SS(BD) = 0.8322$

$(b - 1)(d - 1) = 6$

therefore:

$$MS(BD) = \frac{0.8322}{6} = 0.1387$$

using Equation 4.69, the test statistic, F, can be expressed as:

$$F = \frac{0.1387}{0.005471454} = 25.35$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.71}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$F(\nu_1 = (b - 1)(d - 1), \nu_2 = abcde(n-1))$

$F_{\alpha = 0.05, 6, 1533} = 2.10$

since $F = 25.35 > F_{\alpha = 0.05, 6, 1533} = 2.10$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 6 by a p-value (Pr > F) of 0.0001 which is less than α =

0.05. Therefore, orientation profiles and control orders interact to contribute to workload as shown in Figure 10.

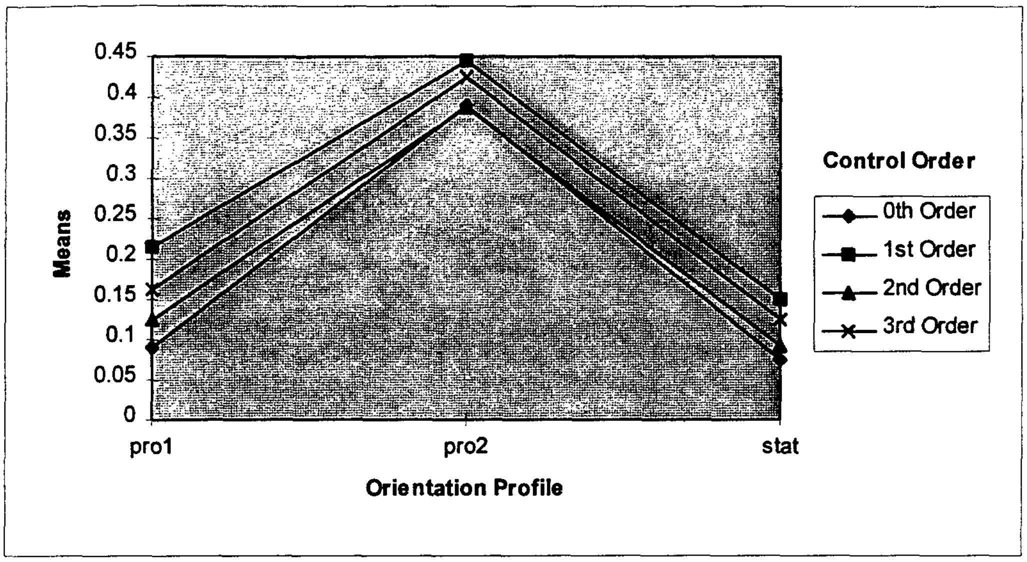

Figure 10. Interaction Between Orientation Profiles and Control Orders

4.2.1.2.8 Test for Factors B and E Interaction

H_o: No interaction between orientation profiles and levels of task difficulty.

H_a: Orientation profiles and levels of task difficulty interact.

$$\text{Test statistic:} \qquad F = \frac{MS(BE)}{MSE} \tag{4.72}$$

using data presented in Table 6, we have

$$MS(BE) = \frac{SS(BE)}{(b-1)(e-1)} \tag{4.73}$$

where:

SS(BE) = 0.05449

$$(b - 1)(e - 1) = 6$$

therefore:

$$MS(BE) = \frac{0.05449}{6} = 0.00908$$

using Equation 4.72, the test statistic, F, can be expressed as:

$$F = \frac{0.00908}{0.005471454} = 1.66$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \qquad (4.74)$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(e - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 6, 1533} = 2.10$$

since $F = 1.66 < F_{\alpha = 0.05, 6, 1533} = 2.10$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 6 by a p-value (Pr > F) of 0.1272 which is more than $\alpha = 0.05$. Hence, there is not sufficient evidence to show that orientation profiles and levels of task difficulty interact to induce workload.

4.2.1.2.9 Test for Factors C and D Interaction

H_o: No interaction between tracking task types and control orders in inducing workload.

H_a: Tracking task types and control orders interact to induce workload.

$$\text{Test statistic:} \qquad F = \frac{MS(CD)}{MSE} \tag{4.75}$$

using data presented in Table 6, we have

$$MS(CD) = \frac{SS(CD)}{(c-1)(d-1)} \tag{4.76}$$

where:

$$SS(CD) = 0.3557$$

$$(c - 1)(d - 1) = 3$$

therefore:

$$MS(CD) = \frac{0.3557}{3} = 0.11857$$

using Equation 4.75, the test statistic, F, can be expressed as:

$$F = \frac{0.11857}{0.005471454} = 21.67$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.77}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (c - 1)(d - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 3, 1533} = 2.60$$

since $F = 21.67 > F_{\alpha = 0.05, 3, 1533} = 2.60$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 6 by a p-value (Pr > F) of 0.0001 which is less than α =

0.05. Thus, there is interaction between tracking task types and control orders in inducing workload as shown in Figure 11.

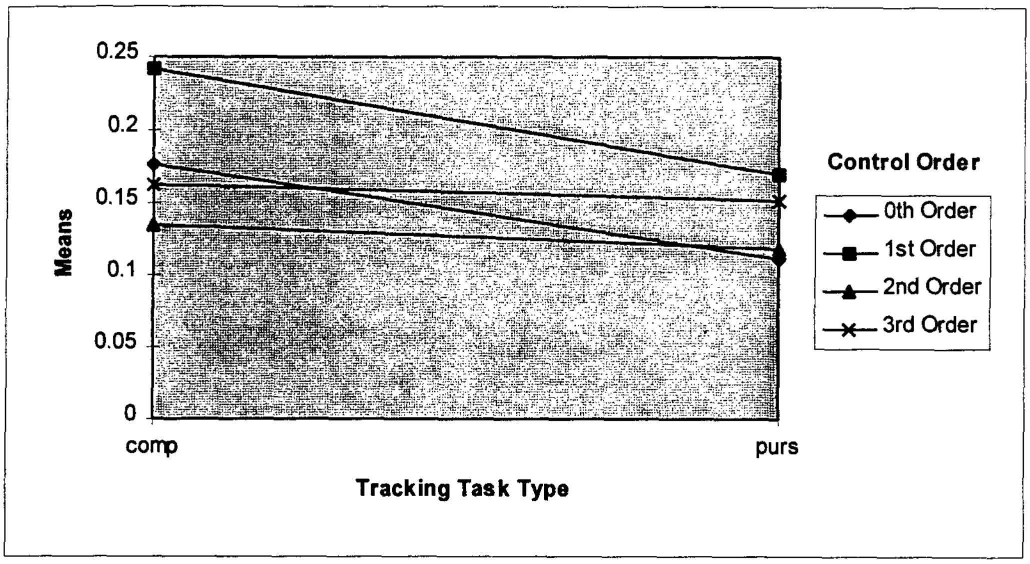

Figure 11. Interaction Between Tracking Task Types and Control Orders

4.2.1.2.10 Test for Factors C and E Interaction

H_o: No interaction between tracking task types and levels of task difficulty in inducing workload.

H_a: Tracking task types and levels of task difficulty interact.

$$\text{Test statistic:} \qquad F = \frac{MS(CE)}{MSE} \tag{4.78}$$

using data presented in Table 6, we have

$$MS(CD) = \frac{SS(CE)}{(c-1)(e-1)} \tag{4.79}$$

where:

$$SS(CE) = 0.0131$$

$$(c - 1)(e - 1) = 3$$

therefore:

$$MS(CD) = \frac{0.0131}{3} = 0.00436$$

using Equation 4.78, the test statistic, F, can be expressed as:

$$F = \frac{0.00436}{0.005471454} = 0.80$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \qquad (4.80)$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (c - 1)(e - 1),\ \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 3, 1533} = 2.60$$

since $F = 0.80 < F_{\alpha = 0.05, 3, 1533} = 2.60$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 6 by a p-value (Pr > F) of 0.4958 which is more than $\alpha = 0.05$. Therefore, no evidence exist to show any interaction between tracking tasks and levels of task difficulty in inducing workload.

4.2.1.2.11 Test for Factors D and E Interaction

H_o: No interaction between control orders and levels of task difficulty in inducing workload.

H_a: Control orders and levels of task difficulty interact to induce workload.

Test statistic: $$F = \frac{MS(DE)}{MSE} \tag{4.81}$$

using data presented in Table 6, we have

$$MS(DE) = \frac{SS(DE)}{(d-1)(e-1)} \tag{4.82}$$

where:

SS(DE) = 0.0985

(d - 1)(e - 1) = 9

therefore:

$$MS(DE) = \frac{0.0985}{9} = 0.01094$$

using Equation 4.81, the test statistic, F, can be expressed as:

$$F = \frac{0.01094}{0.005471454} = 2.00$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.83}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$F(\nu_1 = (d - 1)(e - 1), \nu_2 = abcde(n-1))$

$F_{\alpha = 0.05, 9, 1533} = 1.88$

since $F = 2.00 > F_{\alpha = 0.05, 9, 1533} = 1.88$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 6 by a p-value (Pr > F) of 0.0359 which is less than α =

0.05. Hence, there is interaction between control orders and levels of task difficulty in inducing workload as shown in Figure 12.

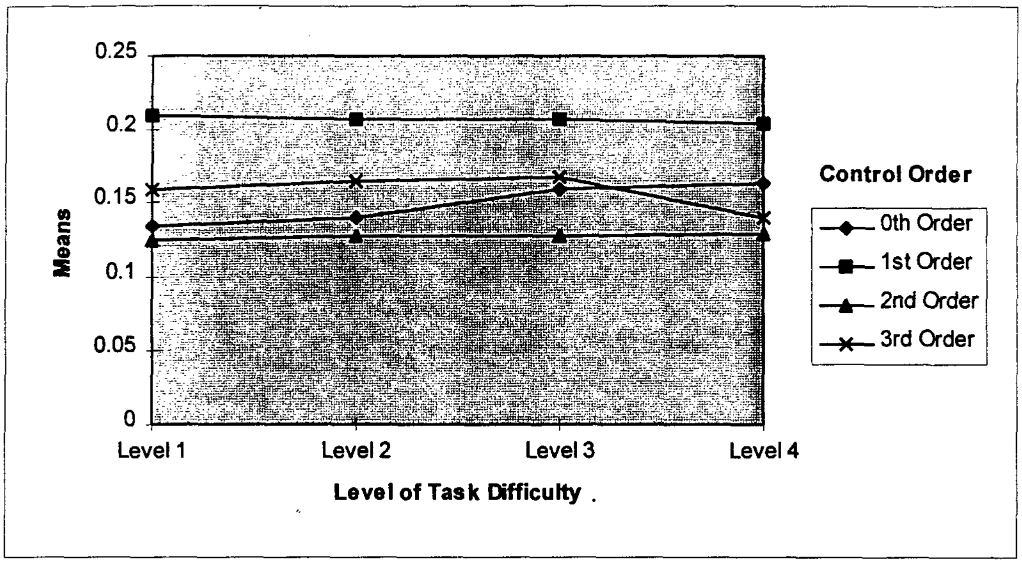

Figure 12. Interaction Between Control Orders and Levels of Task Difficulty

4.2.1.2.12 Test for Factors B, C, and D Interaction

H_o: No interaction between orientation profiles, tracking task types, and control orders in inducing workload.

H_a: Orientation profiles, tracking task types, and control orders interact to induce workload.

Test statistic: $$F = \frac{MS(BCD)}{MSE} \tag{4.84}$$

using data presented in Table 6, we have

$$MS(BCD) = \frac{SS(BCD)}{(b-1)(c-1)(d-1)} \tag{4.85}$$

where:

$$SS(BCD) = 0.2474$$

$$(b - 1)(c - 1)(d - 1) = 5$$

therefore:

$$MS(BCD) = \frac{0.2474}{5} = 0.04948$$

using Equation 4.84, the test statistic, F, can be expressed as:

$$F = \frac{0.04948}{0.005471454} = 9.04$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.86}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(c - 1)(d - 1),\ \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 5, 1533} = 2.21$$

since $F = 9.04 > F_{\alpha = 0.05, 5, 1533} = 2.21$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 6 by a p-value (Pr > F) of 0.0001 which is less than $\alpha = 0.05$. Thus, orientation profiles, tracking task types, and control orders do interact as shown in Figure 13.

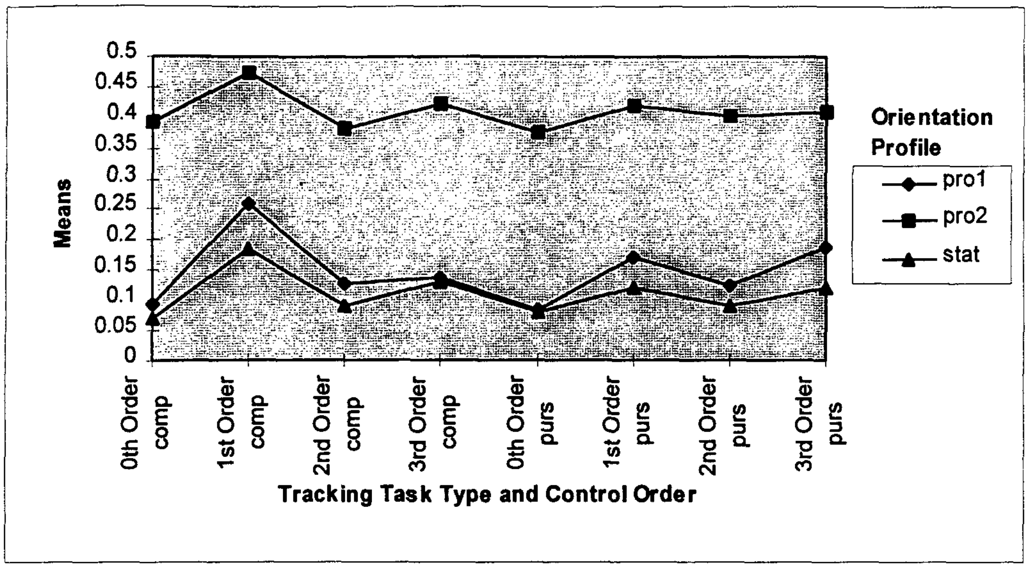

Figure 13. Interaction Between Orientation Profiles, Tracking Task Types, and Control Orders

4.2.1.2.13 Test for Factors B, C, and E Interaction

H_o: No interaction between orientation profiles, tracking task types, and levels of task difficulty in inducing workload.

H_a: Orientation profiles, tracking task types, and levels of task difficulty interact to induce workload.

Test statistic: $$F = \frac{MS(BCE)}{MSE} \tag{4.87}$$

using data presented in Table 6, we have

$$MS(BCD) = \frac{SS(BCE)}{(b-1)(c-1)(e-1)} \tag{4.88}$$

where:

SS(BCE) = 0.0383

(b - 1)(c - 1)(e - 1) = 6

therefore:

$$MS(BCD) = \frac{0.0383}{6} = 0.00638$$

using Equation 4.87, the test statistic, F, can be expressed as:

$$F = \frac{0.00638}{0.005471454} = 1.17$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.89}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(c - 1)(e - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 6, 1533} = 2.10$$

since $F = 1.17 < F_{\alpha = 0.05, 6, 1533} = 2.10$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 6 by a p-value (Pr > F) of 0.3207 which is more than $\alpha = 0.05$. Therefore, orientation profiles, tracking task types, and levels of task difficulty do not interact.

4.2.1.2.14 Test for Factors B, D, and E Interaction

H_o: No interaction between orientation profiles, control orders, and levels of task difficulty in inducing workload.

H_a: Orientation profiles, control orders, and levels of task difficulty interact to induce workload.

Test statistic: $$F = \frac{MS(BDE)}{MSE} \tag{4.90}$$

using data presented in Table 6, we have

$$MS(BCD) = \frac{SS(BDE)}{(b-1)(d-1)(e-1)} \tag{4.91}$$

where:

SS(BDE) = 0.2524

(b - 1)(d - 1)(e - 1) = 18

therefore:

$$MS(BCD) = \frac{0.2524}{18} = 0.014$$

using Equation 4.90, the test statistic, F, can be expressed as:

$$F = \frac{0.014}{0.005471454} = 2.56$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.92}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$F(\nu_1 = (b - 1)(d - 1)(e - 1), \nu_2 = abcde(n-1))$

$F_{\alpha = 0.05, 18, 1533} = 1.57$

since $F = 2.56 > F_{\alpha = 0.05, 18, 1533} = 1.57$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 6 by a p-value (Pr > F) of 0.0003 which is less than α =

0.05. Hence, there is evidence to show orientation profiles, control orders, and levels of task difficulty interact to contribute to workload as shown in Figure 14.

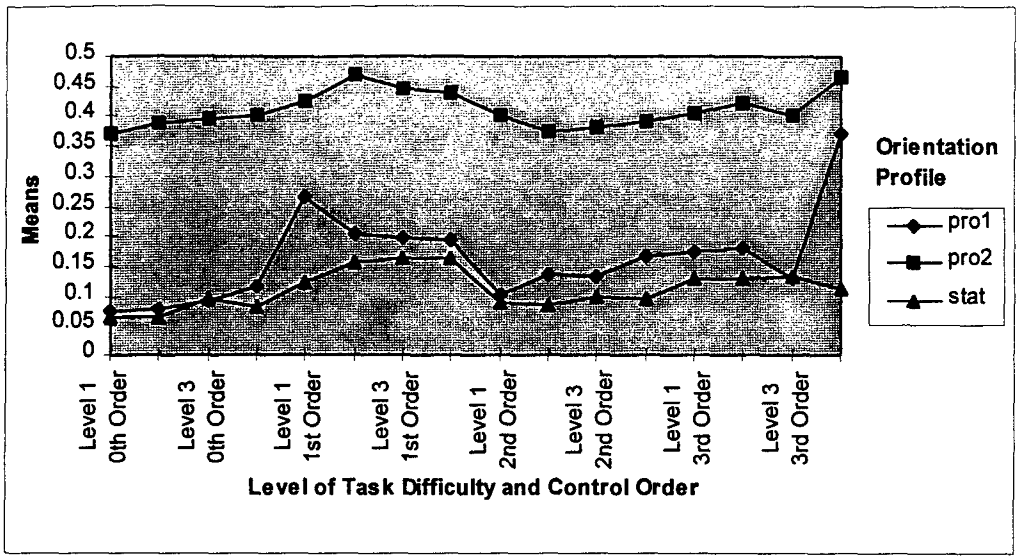

Figure 14. Interaction Between Orientation Profiles, Control Orders, and Levels of Task Difficulty

4.2.1.2.15 Test for Factors C, D, and E Interaction

H_o: No interaction between tracking task types, control orders, and levels of task difficulty in inducing workload.

H_a: Tracking task types, control orders, and levels of task difficulty interact to induce workload.

Test statistic: $$F = \frac{MS(CDE)}{MSE} \tag{4.93}$$

using data presented in Table 6, we have

$$MS(BCD) = \frac{SS(CDE)}{(c-1)(d-1)(e-1)} \tag{4.94}$$

where:

$$SS(CDE) = 0.1824$$

$$(c - 1)(d - 1)(e - 1) = 9$$

therefore:

$$MS(CDE) = \frac{0.1824}{9} = 0.02027$$

using Equation 4.93, the test statistic, F, can be expressed as:

$$F = \frac{0.02027}{0.005471454} = 3.70$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha = 0.05} \tag{4.94}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (c - 1)(d - 1)(e - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 9, 1533} = 1.88$$

since $F = 3.70 > F_{\alpha = 0.05, 9, 1533} = 1.88$, there exist sufficient evidence to reject H_o. This is significant as shown in Table 6 by a p-value (Pr > F) of 0.0001 which is less than $\alpha = 0.05$. Therefore, evidence exists to show that tracking task types, control orders, and levels of task difficulty interact to induce workload as shown in Figure 15.

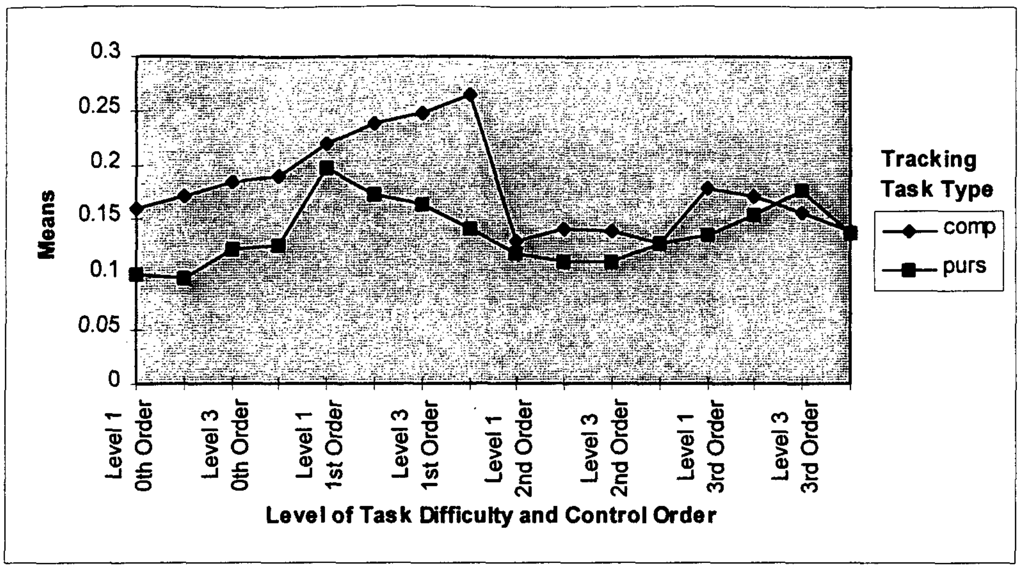

Figure 15. Interaction Between Tracking Task Types, Control Orders, and Levels of Task Difficulty

4.2.1.2.16 Test for Factors B, C, D, and E Interaction

H_o: No interaction between orientation profiles, tracking task types, control orders, and levels of task difficulty.

H_a: Orientation profiles, tracking task types, control orders, and levels of task difficulty interact.

Test statistic: $$F = \frac{MS(BCDE)}{MSE} \tag{4.96}$$

using data presented in Table 6, we have

$$MS(BCD) = \frac{SS(BCDE)}{(b-1)(c-1)(d-1)(e-1)} \tag{4.97}$$

where:

SS(BCDE) = 0.0876

(b - 1)(c - 1)(d - 1)(e - 1) = 13

therefore:

$$MS(BCDE) = \frac{0.0876}{13} = 0.00674$$

using Equation 4.96, the test statistic, F, can be expressed as:

$$F = \frac{0.00674}{0.005471454} = 1.23$$

the rejection region, at level $\alpha = 0.05$, is expressed as:

$$F > F_{\alpha=0.05} \tag{4.98}$$

where:

F has ν_1 and ν_2 degrees of freedom respectively, that is:

$$F(\nu_1 = (b - 1)(c - 1)(d - 1)(e - 1), \nu_2 = abcde(n-1))$$

$$F_{\alpha = 0.05, 13, 1533} = 1.75$$

since $F = 1.23 < F_{\alpha = 0.05, 13, 1533} = 1.75$, there exist sufficient evidence to accept H_o. This is not significant as shown in Table 6 by a p-value (Pr > F) of 0.2504 which is more than $\alpha = 0.05$. Hence, there is not evidence to show interaction between orientation profiles, tracking task types, control orders, and levels of task difficulty

4.2.2 Tukey Test: Comparison of Means

Based on the studentized range statistic, the Tukey Test is a multiple comparison procedure for comparing the significant differences between means. This test controls the type I experimentwise error rate. It declares two means significantly different based on the absolute value of their sample differences. It is applied to cases where significant differences are suspected. The following sections discuss the results of the Tukey Test as provided by SAS™ [1990].

4.2.2.1 Tukey Test for Complexity Parameter

4.2.2.1.1 Test of Subject Means

There is a significant difference between Subject #1 and Subject #2. By using the data presented in Table 7, we have a confidence interval of

$$0.03365 \leq 0.09501 \leq 0.15638$$

which does not cover zero. Furthermore, the mean for subject #1 is significantly higher than Subject #2 because the control limits are positive. Similarly, the following differences in means for the complexity parameter are shown in Table 7:

Subjects	#1 and #3
	#1 and #4
	#1 and #5
	#2 and #3
	#2 and #5
	#3 and #4
	#3 and #5

Table 7. Tukey Test for Complexity Parameter Comparison of Means Analysis: Subjects

Tukey's Studentized Range (HSD) Test for variable: CP

NOTE: This test controls the type I experimentwise error rate.

Alpha= 0.05 Confidence= 0.95 df= 1533 MSE= 0.054935
Critical Value of Studentized Range= 3.862

Comparisons significant at the 0.05 level are indicated by '***'.

SUBJECT Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit	
1 - 2	0.03365	0.09501	0.15638	***
1 - 3	0.04901	0.09507	0.14114	***
1 - 4	0.10126	0.15035	0.19945	***
1 - 5	0.13496	0.18405	0.23315	***
2 - 1	-0.15638	-0.09501	-0.03365	***
2 - 3	-0.05891	0.00006	0.05903	
2 - 4	-0.00603	0.05534	0.11671	
2 - 5	0.02767	0.08904	0.15041	***
3 - 1	-0.14114	-0.09507	-0.04901	***
3 - 2	-0.05903	-0.00006	0.05891	
3 - 4	0.00922	0.05528	0.10134	***
3 - 5	0.04292	0.08898	0.13504	***
4 - 1	-0.19945	-0.15035	-0.10126	***
4 - 2	-0.11671	-0.05534	0.00603	
4 - 3	-0.10134	-0.05528	-0.00922	***
4 - 5	-0.01539	0.03370	0.08279	
5 - 1	-0.23315	-0.18405	-0.13496	***
5 - 2	-0.15041	-0.08904	-0.02767	***
5 - 3	-0.13504	-0.08898	-0.04292	***
5 - 4	-0.08279	-0.03370	0.01539	

4.2.2.1.2 Test of Orientation Profile Means

There is a significant difference between the stationary orientation profile (stat) and motion profile #1 (pro1) (see Table 8). Furthermore, the mean for motion profile #1 is significantly higher than the stationary orientation because the control limits are negative.

There was no significant difference between the:

stationary orientation profile (stat) and motion profile #2 (pro2)

motion profile #1 (pro1) and motion profile #2 (pro2).

Table 8. Tukey Test for Complexity Parameter Comparison of Means: Orientation Profile

Tukey's Studentized Range (HSD) Test for variable: CP

NOTE: This test controls the type I experimentwise error rate.

Alpha= 0.05 Confidence= 0.95 df= 1533 MSE= 0.054935
Critical Value of Studentized Range= 3.318

Comparisons significant at the 0.05 level are indicated by '***'.

ORIENT Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit	
pro1 - pro2	-0.02427	0.02144	0.06715	
pro1 - stat	0.01862	0.04778	0.07694	***
pro2 - pro1	-0.06715	-0.02144	0.02427	
pro2 - stat	-0.01832	0.02635	0.07101	
stat - pro1	-0.07694	-0.04778	-0.01862	***
stat - pro2	-0.07101	-0.02635	0.01832	

4.2.2.1.3 Test of TrackingTask Means

There is a significant difference between compensatory and pursuit tracking tasks. By using the Tukey Grouping generated by the SAS program (see Table 9), means that are not significantly different are grouped together and assigned the same letter. The Tukey grouping letter for compensatory tracking (A) differs from that of pursuit tracking (B) showing that their means differ significantly.

Table 9. Tukey Test for Complexity Parameter Comparison of Means Analysis: Tracking Task

```
   Tukey's Studentized Range (HSD) Test for variable: CP

NOTE: This test controls the type I experimentwise error rate, but
      generally has a higher type II error rate than REGWQ.

              Alpha= 0.05  df= 1533  MSE= 0.054935
           Critical Value of Studentized Range= 2.774
             Minimum Significant Difference= 0.0228
               WARNING: Cell sizes are not equal.
              Harmonic Mean of cell sizes= 810.842

Means with the same letter are not significantly different.

       Tukey Grouping              Mean       N  TASK

                    A           0.44480     860  comp

                    B           0.39861     767  purs
```

4.2.2.1.4 Test of Control Order Means

There is a significant difference between 0th and 1st control order (see Table 10). Furthermore, the mean for the 1st order is significantly higher than the 0th order because the control limits are negative. Similarly, the following mean differences were observed:

0th and 2nd order control

0th and 3rd order control

1st and 2nd order control

1st and 3rd order control

2nd and 3rd order control

Table 10. Tukey Test for Complexity Parameter Comparison of Means Analysis: Control Order

Tukey's Studentized Range (HSD) Test for variable: CP

NOTE: This test controls the type I experimentwise error rate.

Alpha= 0.05 Confidence= 0.95 df= 1533 MSE= 0.054935
Critical Value of Studentized Range= 3.637

Comparisons significant at the 0.05 level are indicated by '***'.

ORDER Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit	
1 - 3	0.05878	0.10196	0.14514	***
1 - 2	0.15276	0.19574	0.23872	***
1 - 0	0.21273	0.25394	0.29515	***
3 - 1	-0.14514	-0.10196	-0.05878	***
3 - 2	0.05025	0.09378	0.13732	***
3 - 0	0.11019	0.15198	0.19377	***
2 - 1	-0.23872	-0.19574	-0.15276	***
2 - 3	-0.13732	-0.09378	-0.05025	***
2 - 0	0.01662	0.05820	0.09978	***
0 - 1	-0.29515	-0.25394	-0.21273	***
0 - 3	-0.19377	-0.15198	-0.11019	***
0 - 2	-0.09978	-0.05820	-0.01662	***

4.2.2.1.5 Test of Level of Difficulty Means

There is no significant difference between level 1 and level 2 (see Table 11).

Similarly, there was no mean differences between and among the task difficulty levels.

Table 11. Tukey Test for Complexity Parameter Comparison of Means Analysis: Level of Difficulty

Tukey's Studentized Range (HSD) Test for variable: CP

NOTE: This test controls the type I experimentwise error rate.

Alpha= 0.05 Confidence= 0.95 df= 1533 MSE= 0.054935
Critical Value of Studentized Range= 3.637

Comparisons significant at the 0.05 level are indicated by '***'.

LEVEL Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit
3 - 4	-0.03252	0.00984	0.05220
3 - 2	-0.02668	0.01563	0.05794
3 - 1	-0.00591	0.03633	0.07856
4 - 3	-0.05220	-0.00984	0.03252
4 - 2	-0.03652	0.00579	0.04810
4 - 1	-0.01575	0.02648	0.06872
2 - 3	-0.05794	-0.01563	0.02668
2 - 4	-0.04810	-0.00579	0.03652
2 - 1	-0.02148	0.02070	0.06288
1 - 3	-0.07856	-0.03633	0.00591
1 - 4	-0.06872	-0.02648	0.01575
1 - 2	-0.06288	-0.02070	0.02148

4.2.2.2 Tukey Test for Workload Index

4.2.2.2.1 Test of Subject Means

There is a significant difference between Subject #1 and Subject #2 (see Table 12). Furthermore, the mean for subject #1 is significantly higher than Subject #2 because the control limits are positive. Similarly, the following differences in means for the workload index are shown in Table 12:

Table 12. Tukey Test for Workload Index Comparison of Means Analysis: Subjects

Tukey's Studentized Range (HSD) Test for variable: WL

NOTE: This test controls the type I experimentwise error rate.

Alpha= 0.05 Confidence= 0.95 df= 1533 MSE= 0.005471
Critical Value of Studentized Range= 3.862

Comparisons significant at the 0.05 level are indicated by '***'.

SUBJECT Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit	
3 - 1	0.009682	0.024219	0.038756	***
3 - 4	0.072015	0.086552	0.101089	***
3 - 2	0.073517	0.092128	0.110739	***
3 - 5	0.080617	0.095155	0.109692	***
1 - 3	-0.038756	-0.024219	-0.009682	***
1 - 4	0.046839	0.062332	0.077826	***
1 - 2	0.048541	0.067908	0.087276	***
1 - 5	0.055441	0.070935	0.086429	***
4 - 3	-0.101089	-0.086552	-0.072015	***
4 - 1	-0.077826	-0.062332	-0.046839	***
4 - 2	-0.013791	0.005576	0.024943	
4 - 5	-0.006891	0.008603	0.024097	
2 - 3	-0.110739	-0.092128	-0.073517	***
2 - 1	-0.087276	-0.067908	-0.048541	***
2 - 4	-0.024943	-0.005576	0.013791	
2 - 5	-0.016340	0.003027	0.022394	
5 - 3	-0.109692	-0.095155	-0.080617	***
5 - 1	-0.086429	-0.070935	-0.055441	***
5 - 4	-0.024097	-0.008603	0.006891	
5 - 2	-0.022394	-0.003027	0.016340	

Subjects #1 and #3

#1 and #4

#1 and #5

#2 and #3

#3 and #4

#3 and #5

There is no significant difference between Subject #2 and Subject #4. The same is also shown in Table 12 for subjects:

#2 and #5

#4 and #5

4.2.2.1.2 Test of Orientation Means

There is a significant difference between the stationary orientation (stat) and motion profile #1 (pro1). Furthermore, the mean for motion profile #1 is significantly higher than the stationary orientation. Similarly, the following differences are observed:

stationary orientation and motion profile #2 (pro2)

motion profile #1 and motion profile #2

Furthermore, the mean for motion profile #2 is significantly higher than motion profile #1 because the control limits are negative.

Table 13. Tukey Test for Workload Index Comparison of Means Analysis:
Orientation Profile

```
Tukey's Studentized Range (HSD) Test for variable: WL

NOTE: This test controls the type I experimentwise error rate.

Alpha= 0.05  Confidence= 0.95  df= 1533  MSE= 0.005471
       Critical Value of Studentized Range= 3.318

Comparisons significant at the 0.05 level are indicated by '***'.
```

ORIENT Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit	
pro2 - pro1	0.241669	0.256094	0.270519	***
pro2 - stat	0.279584	0.293679	0.307774	***
pro1 - pro2	-0.270519	-0.256094	-0.241669	***
pro1 - stat	0.028382	0.037585	0.046788	***
stat - pro2	-0.307774	-0.293679	-0.279584	***
stat - pro1	-0.046788	-0.037585	-0.028382	***

4.2.2.1.3 Test of TrackingTask Means

There is a significant difference between compensatory and pursuit tracking tasks. By using the Tukey Grouping (see Table 14) generated by the SAS program, variables with means that are not significantly different are grouped together and assigned the same letter. The variables comp and purs do not have the same letter; therefore, their means differ significantly.

Table 14. Tukey Test for Workload Index Comparison of Means Analysis: Tracking Task

```
Tukey's Studentized Range (HSD) Test for variable: WL

NOTE: This test controls the type I experimentwise error rate, but
      generally has a higher type II error rate than REGWQ.

            Alpha= 0.05  df= 1533  MSE= 0.005471
        Critical Value of Studentized Range= 2.774
          Minimum Significant Difference= 0.0072
            WARNING: Cell sizes are not equal.
           Harmonic Mean of cell sizes= 810.842

Means with the same letter are not significantly different.
```

Tukey Grouping	Mean	N	TASK
A	0.178786	860	comp
B	0.137538	767	purs

4.2.2.1.4 Test of Control Tracking Order Means

There is a significant difference between 0th and 1st control order. The mean for the 1st order is significantly higher than the 0th order because the control limits are negative. Similarly, the following mean differences for workload index are shown in Table 15:

0th and 2nd order control

1st and 2nd order control

1st and 3rd order control

2nd and 3rd order control

There is no significant difference between 0th and 3rd control order.

Table 15. Tukey Test for Workload Index Comparison of Means Analysis: Control Order

Tukey's Studentized Range (HSD) Test for variable: WL

NOTE: This test controls the type I experimentwise error rate.

Alpha= 0.05 Confidence= 0.95 df= 1533 MSE= 0.005471
Critical Value of Studentized Range= 3.637

Comparisons significant at the 0.05 level are indicated by '***'.

ORDER Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit	
1 - 3	0.035275	0.048903	0.062531	***
1 - 0	0.044704	0.057710	0.070716	***
1 - 2	0.065750	0.079315	0.092879	***
3 - 1	-0.062531	-0.048903	-0.035275	***
3 - 0	-0.004381	0.008807	0.021995	
3 - 2	0.016672	0.030412	0.044151	***
0 - 1	-0.070716	-0.057710	-0.044704	***
0 - 3	-0.021995	-0.008807	0.004381	
0 - 2	0.008482	0.021604	0.034727	***
2 - 1	-0.092879	-0.079315	-0.065750	***
2 - 3	-0.044151	-0.030412	-0.016672	***
2 - 0	-0.034727	-0.021604	-0.008482	***

4.2.2.1.5 Test of Level of Difficulty Means

There is no significant difference between level 1 and level 2. Similarly, there was no mean differences between and among the task difficulty levels for workload index.

Table 16. Tukey Test for Workload Index Comparison of Means Analysis: Level of Difficulty

Tukey's Studentized Range (HSD) Test for variable: WL

NOTE: This test controls the type I experimentwise error rate.

Alpha= 0.05 Confidence= 0.95 df= 1533 MSE= 0.005471
Critical Value of Studentized Range= 3.637

Comparisons significant at the 0.05 level are indicated by '***'.

LEVEL Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit
3 - 4	-0.007648	0.005721	0.019090
3 - 2	-0.007419	0.005933	0.019286
3 - 1	-0.004598	0.008730	0.022058
4 - 3	-0.019090	-0.005721	0.007648
4 - 2	-0.013140	0.000212	0.013565
4 - 1	-0.010319	0.003009	0.016337
2 - 3	-0.019286	-0.005933	0.007419
2 - 4	-0.013565	-0.000212	0.013140
2 - 1	-0.010515	0.002796	0.016108
1 - 3	-0.022058	-0.008730	0.004598
1 - 4	-0.016337	-0.003009	0.010319
1 - 2	-0.016108	-0.002796	0.010515

CHAPTER FIVE

Summary, Conclusions, and Recommendations

5.1 Summary

The purpose of this thesis was to investigate through laboratory experiments the effects of induced motion during tracking task performance on pilot workload as well as the system complexity. Using Equation 2.7 to calculate complexity parameters and Equation 2.3 to calculate workload indexes, analysis was done to determine: differences in the complexity parameter and workload index when tracking tasks were performed. The observations were done with and without motion, with compensatory and pursuit tracking tasks, and with tracking tasks under zero, first, second, and third control order.

5.2 Observations and Conclusions

5.2.1 Discussion of Analysis of Variance Results

An ANOVA test was used to determine if there was sufficient evidence to conclude that performance of tracking tasks during motion effects workload and system complexity at a significance level of $\alpha = 0.05$.

5.2.1.1 Discussion of ANOVA for Complexity Parameter

The following results were obtained:

(1) At least two of the orientation profile means show significantly differences.

(2) There is a significant difference in the complexity parameter means for compensatory and pursuit tracking tasks. The complexity parameter is used as a measure of error (signal)-noise ratio.

(3) At least two of the control order means are significantly different.

(4) There is interaction between the orientation profiles and control order modalities.

(5) There is interaction between the tracking task types and control order modalities.

(6) There is interaction between the orientation profiles, control order modalities, and levels of task difficulty.

(7) There is interaction between the tracking task types, control order modalities, and levels of task difficulty.

In conclusion, performing tracking tasks during induced motion may increase task execution error generated by the human, which in turn affects error-signal ratio known as task complexity. System complexity or error ratio differs between compensatory and pursuit tracking tasks as well as among the control order modalities. Furthermore, various combinations of orientation profiles and control orders affect system complexity; although the ANOVA does not show which combinations are significant. The same is true for combinations of the following:

(a) tracking task types and control orders,

(b) orientation profiles, control orders, and levels of task difficulty, and

(c) tracking task types, control orders, and levels of task difficulty.

5.2.1.2 Discussion of ANOVA for Workload Index

The following results were obtained:

(1) At least two of the orientation profile means are significantly different.

(2) There is a significant difference in the mean workload index for compensatory and pursuit tracking tasks.

(3) At least two of the workload means from control order are significantly different.

(4) There is interaction between the orientation profiles and control order modalities.

(5) There is interaction between the tracking task types and control order modalities.

(6) There is interaction between the orientation profiles, tracking task types, and control order modalities.

(7) There is interaction between the orientation profiles, control order modalities, and levels of task difficulty.

(8) There is interaction between the tracking task types, control order modalities, and levels of task difficulties.

In conclusion, performing tracking tasks during induced motion does affect workload. The workload index differs between compensatory and pursuit tracking tasks as well as among the control order modalities. Furthermore, various combinations of orientation profiles and control orders affect the workload index; although the ANOVA does not show which combinations are significant. The same is true for the following:

(a) tracking task types and control orders,

(b) orientation profiles, tracking task types, and levels of task difficulty,

(c) orientation profiles, control orders, and levels of task difficulty, and

(d) tracking task types, control orders, and levels of task difficulty.

5.2.2 Discussion of Tukey Test Results

A Tukey Test was used to determine which mean values within a factor were significant.

5.2.2.1 Discussion of Tukey Test Results for Complexity Parameter

The following results were obtained:

(1) There is a significant difference between the stationary orientation profile and motion profile #1. Furthermore, the complexity parameter mean for motion profile #1 is significantly higher than that of the stationary orientation profile.

(2) There is a significant difference between compensatory tracking tasks and pursuit tracking tasks.

(3) There is a significant difference between all control modalities. Furthermore, the complexity parameter mean for the 1st order control is significantly higer than that of the 3rd order control. The mean for the 3rd order control is significantly higher than that of the 2nd order control. Similarly, the mean for the 2nd order control is significantly higher than that of the 0th order control.

In conclusion, system complexity is affected by induced motion. Although the Tukey Test shows a significant difference between the stationary orientation profile and motion profile #1, it does not show a significant difference between:

(a) the stationary orientation profile and motion profile #2, and

(b) motion profile #1 and motion profile #2.

However, there is a difference in system complexity when performing compensatory tracking tasks versus pursuit tracking tasks. Furthermore, system complexity is affected by the control order modality of the tracking task.

5.2.2.2 Discussion of Tukey Test Results for Workload Index

The following results were obtained:

(1) There is a significant difference between all orientation profiles. Furthermore, the workload mean for motion profile #2 is significantly higher than motion profile #1. Similarly, the mean for motion profile #1 is significantly higher than that of the stationary orientation profile.

(2) There is a significant difference between the workload means for compensatory tracking tasks and pursuit tracking tasks.

(3) There is not a significant difference in workload mean for the 0th and 3rd order controls. However, the mean for the 1st order control is significantly than the 0th and 3rd order control . Furthermore, the means for the 0th and 3rd order control are significantly higher that that of the 2nd order control.

In conclusion, the workload index is affected by induced motion during task performance. The Tukey test shows that the order of significance of the orientation profiles is as follows: stationary orientation profile (b = 0), motion profile #1 (b = 0.85), and motion profile #2 (b = 2). Therefore, the workload index is affected significantly as the damping coefficient of the system increases. As with system complexity, the workload index is affected by the type of tracking task being performed.

5.3 Recommendations for Further Research

In view of the observations from this thesis work, the following recommendations are given for further study:

(1) Determine the minimum and maximum workload index levels for various orientation profiles, tracking task types, and order control modality combinations.

(2) Study the effects of performing secondary tasks during induced motion, and develop a workload index for multitask situations.

(3) Investigate the effects induced motion on system complexity and workload index for three degrees of freedom simulated with yaw motion.

(4) Expand the quantitative workload metric to include time as a measure of dynamic workload.

(5) Investigate how to use the mental and physiological indicators as parameters of the quantitative workload metric.

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APPENDIX A:

A Model for Workload Change Based on System Complexity

INTEGRATION OF WORKLOAD INDEX EQUATION

$$\text{WL} = \begin{cases} \dfrac{c-\sqrt{e^{-a}}}{c+e^{-a}}, & \textit{for } b = 0 \\[2ex] \dfrac{c-\dfrac{1}{b}e^{-a}}{c+e^{-a}}, & \textit{for } b > 0 \end{cases}$$

c = work content (constant)

b = damping coefficient (constant)

a = complexity parameter (variable)

For b = 0:

$$\text{WL}\Delta\text{a} = \int_{a_1}^{a_2} \frac{c-\sqrt{e^{-a}}}{c+e^{-a}} da$$

Let c = 1; therefore,

$$= \int_{a_1}^{a_2} \frac{1-\sqrt{e^{-a}}}{1+e^{-a}} da = \int_{a_1}^{a_2} \frac{1}{1+e^{-a}} da - \int_{a_1}^{a_2} \frac{(e^{-a})^{\frac{1}{2}}}{1+e^{-a}} da$$

So,

$$\text{A} = \int_{a_1}^{a_2} \frac{1}{1+e^{-a}} da \quad \text{and} \quad \text{B} = \int_{a_1}^{a_2} \frac{(e^{-a})^{\frac{1}{2}}}{1+e^{-a}} da$$

$$\text{A} = \int_{a_1}^{a_2} \frac{1}{1+e^{-a}} da = \int_{a_1}^{a_2} \frac{1+e^{-a}-e^{-a}}{1+e^{-a}} da = \int_{a_1}^{a_2} \frac{1+e^{-a}}{1+e^{-a}} da + \int_{a_1}^{a_2} \frac{-e^{-a}}{1+e^{-a}} da$$

$$= \int_{a_1}^{a_2} da + \int_{a_1}^{a_2} \frac{du}{u}$$

$$= \; a + \ln(1+e^{-a})]_{a_1}^{a_2}$$

Hence,

$$\mathrm{A} = \; a + \ln(c + e^{-a})\Big]_{a_1}^{a_2}$$

Now,

$$\mathrm{B} = \int_{a_1}^{a_2} \frac{(e^{-a})^{\frac{1}{2}}}{1+e^{-a}}\,da \; = \; \int_{a_1}^{a_2} \frac{e^{-\frac{1}{2}a}}{1+e^{-a}}\,da \; = \; -2\int_{a_1}^{a_2} \frac{du}{1+u^2} = \; -2\arctan u]_{a_1}^{a_2}$$

$$= \; -2\arctan e^{-\frac{1}{2}a}\,]_{a_1}^{a_2}$$

$$= \; -2\int_{a_1}^{a_2} \frac{du}{c+u^2}$$

$$= \; -2\left(\frac{1}{\sqrt{c}}\arctan\left(\frac{u}{\sqrt{c}}\right)\right)\,]_{a_1}^{a_2}$$

NOTE: $u = e^{-\frac{1}{2}a}$

$$du = -\frac{1}{2}e^{-\frac{1}{2}a}\,da$$

$$-2du = e^{-\frac{1}{2}a}\,da$$

$$e^{-a} \; = (e^{-\frac{1}{2}a})^2$$

Hence,

$$\mathrm{B} = \frac{-2}{\sqrt{c}}\arctan\frac{e^{-\frac{1}{2}a}}{\sqrt{c}}]_{a_1}^{a_2}$$

Therefore, for b = 0

WLΔa = A - B

$$\text{WL}\Delta\text{a} = \left[\left(a+\ln(c+e^{-a})\right)-\left(\frac{-2}{\sqrt{c}}\arctan\frac{e^{-\frac{1}{2}a}}{\sqrt{c}}\right)\right]_{a_1}^{a_2}$$

For b > 0:

$$\text{WL}\Delta\text{a} = \int_{a_1}^{a_2}\frac{c-\frac{1}{b}e^{-a}}{c+e^{-a}}$$

Let c = 1; therefore,

$$= \int_{a_1}^{a_2}\frac{1-\frac{1}{b}e^{-a}}{1+e^{-a}}da = \int_{a_1}^{a_2}\frac{1}{1+e^{-a}}da + \frac{1}{b}\int_{a_1}^{a_2}\frac{-e^{-a}}{1+e^{-a}}da$$

So,

$$A = \int_{a_1}^{a_2}\frac{1}{1+e^{-a}}da \quad \text{and} \quad B = \frac{1}{b}\int_{a_1}^{a_2}\frac{-e^{-a}}{1+e^{-a}}da$$

$$A = \int_{a_1}^{a_2}\frac{1}{1+e^{-a}}da = \int_{a_1}^{a_2}\frac{1+e^{-a}-e^{-a}}{1+e^{-a}}da = \int_{a_1}^{a_2}\frac{1+e^{-a}}{1+e^{-a}}da + \int_{a_1}^{a_2}\frac{-e^{-a}}{1+e^{-a}}da$$

$$= \int_{a_1}^{a_2}da + \int_{a_1}^{a_2}\frac{du}{u}$$

$$= a+\ln(1+e^{-a})]_{a_1}^{a_2}$$

Hence,

$$A = a + \ln(c + e^{-a})\Big]_{a_1}^{a_2}$$

Now,

$$B = \frac{1}{b}\int_{a_1}^{a_2} \frac{-e^{-a}}{1+e^{-a}}\,da = \frac{1}{b}\int_{a_1}^{a_2} \frac{du}{u} = \frac{1}{b}\ln(1+e^{-a})$$

Hence,

$$B = \frac{1}{b}\ln(c + e^{-a})$$

Therefore, for $b > 0$

WLΔa = A + B

$$\text{WL}\Delta\text{a} = \left[(a + \ln(c + e^{-a})) + (\frac{1}{b}\ln(c + e^{-a}))\right]_{a_1}^{a_2}$$

APPENDIX B:

Sample Subject Consent Forms

PARTICIPATION IN EXPERIMENTS
(The Effects of Motion During Task Performance on Pilot Workload)

Consent Form

I, Tracey E. [illegible], consent to perform in the above mentioned experiment. I will receive no compensation for my participation.

Accordingly, I fully understand and will abide by all applicable safety rules. Additionally, I understand I am liable for participation to the full extent of all applicable Laws.

Signed: [illegible]

Date: [illegible]

Witness: [illegible]

INSTRUCTIONS FOR EXPERIMENTS
(The Effects of Motion During Task Performance on Pilot Workload)

I would like to thank you for taking the time to participate in this experiment. Your participation will aid in the extensive research being done in the Industrial Engineering Department at North Carolina Agricultural and Technical State University for NASA and their future endeavors. Please read these experimental instructions carefully. Make sure you understand fully what is expected of you. The experiment director will explain what you are expected to do in detail. Then the experiment director will review and summarize what is expected of you before each experimental set begins to refresh your memory.

ALEXANDRIA R. WATSON, 1LT, USAF
AFIT/CI Student

Experiment Overview

The goal of this experiment is to investigate how workload is affected by performing manual control tracking tasks while in motion. The experiment has two parts.

Part A: Perform compensatory and pursuit tracking tasks while in a stationary position.

Part B: Perform compensatory and pursuit tracking tasks while in motion on the Aggie Flight Simulator Platform.

All tracking tasks are to be done at peek performance.

Safety Rules

* Please follow all laboratory rules.
* Do not use simulator platform or any equipment without the supervision of the experiment director.
* The helmet must be worn at all times while utilizing the simulator platform as well as safety restraints.
* Be aware of safety zones in the laboratory and on all equipment.

Goal of Tracking Tasks

The goal of compensatory and pursuit tracking tasks is to keep the vertical line on the screen (by manipulating the mouse) in the target box for the duration of the trial.

Statement of Understanding

I, Tracey E. Bell, fully understand what is expected of me for this experiment as well as the safety rules listed above. Any errors made by me in this experiment will not be due to lack of knowledge or understanding of my role in this experiment.

Signed: Tracey E. Bell

Date: 4-19-96

Witness:

APPENDIX C:

Sample Data Collected from Experiment

Subject #: 1 **Damping Coefficient:** 0

Compensatory Tracking

0th Order	Level 1	Trial	MeanEr	RmsEr	SdEr	RmsStk	RmsStkVel
		1	31.070	0.061	0.133	0.021	0.062
		2	39.870	0.015	0.096	0.018	0.061
		3	38.670	-0.007	0.108	0.016	0.071
		4	38.400	0.038	0.123	0.024	0.085
		5	21.470	-0.007	0.206	0.041	0.183
	Level 2	1	29.330	0.031	0.109	0.014	0.052
		2	28.400	0.041	0.326	0.058	0.224
		3	24.530	0.005	0.153	0.026	0.066
		4	40.270	0.027	0.107	0.010	0.019
		5	16.670	0.056	0.141	0.022	0.065
	Level 3	1	15.730	0.116	0.228	0.033	0.069
		2	8.270	0.166	0.349	0.055	0.107
		3	16.930	0.057	0.232	0.021	0.046
		4	14.930	0.069	0.225	0.042	0.106
		5	20.000	0.087	0.263	0.035	0.082
	Level 4	1	4.930	0.186	2.072	0.383	1.890
		2	7.870	0.027	0.554	0.047	0.121
		3	10.130	0.065	0.441	0.024	0.048
		4	6.930	0.016	0.455	0.021	0.072
		5	4.930	0.060	0.492	0.029	0.075
1st Order	Level 1	1	64.130	0.001	0.052	0.006	0.009
		2	50.000	0.000	0.065	0.005	0.017
		3	59.330	0.000	0.058	0.002	0.007
		4	28.400	0.001	0.058	0.013	0.029
		5	65.470	0.009	0.059	0.052	0.031
	Level 2	1	40.270	0.003	0.094	0.018	0.016
		2	40.670	0.009	0.084	0.048	0.019
		3	42.670	0.001	0.089	0.008	0.020
		4	37.600	0.002	0.090	0.010	0.007
		5	39.470	0.009	0.089	0.054	0.027
	Level 3	1	15.730	0.003	0.187	0.030	0.029
		2	19.600	-0.003	0.167	0.020	0.017
		3	21.600	0.037	0.192	0.214	0.053
		4	19.070	0.007	0.176	0.038	0.027
		5	16.400	-0.002	0.207	0.024	0.030
	Level 4	1	8.670	0.034	0.449	0.224	0.194
		2	5.330	0.017	0.509	0.105	0.049
		3	7.730	0.008	0.430	0.054	0.071
		4	7.070	-0.003	0.498	0.033	0.034
		5	9.730	0.027	0.481	0.147	0.053
2nd Order	Level 1	1	100.000	0.001	0.059	0.013	0.028
		2	100.000	0.006	0.052	0.019	0.058
		3	100.000	0.008	0.053	0.056	0.158
		4	100.000	0.005	0.065	0.069	0.158
		5	94.930	0.101	0.071	0.094	0.203

	Level 2	1	100.000	0.002	0.082	0.045	0.101
		2	100.000	0.009	0.098	0.034	0.073
		3	92.130	0.016	0.102	0.086	0.165
		4	100.000	0.008	0.092	0.011	0.026
		5	97.870	0.010	0.101	0.117	0.279
	Level 3	1	100.000	0.004	0.177	0.040	0.071
		2	100.000	0.004	0.188	0.040	0.080
		3	100.000	-0.004	0.182	0.015	0.031
		4	78.520	0.022	0.166	0.156	0.243
		5	92.400	0.019	0.174	0.136	0.316
	Level 4	1	49.470	-0.047	0.483	0.136	0.282
		2	19.200	0.067	0.456	0.471	1.782
		3	24.270	0.149	0.555	0.573	1.573
		4	40.800	-0.122	0.486	0.674	3.532
		5	43.200	0.019	0.479	0.129	0.342
3rd Order	Level 1	1	66.530	0.039	0.188	0.522	1.660
		2	44.800	-0.402	0.636	0.800	4.185
		3	39.470	0.061	0.212	0.773	4.548
		4	81.600	0.003	0.068	0.416	1.007
		5	100.000	0.001	0.064	0.020	0.045
	Level 2	1	36.800	0.597	0.977	0.860	7.715
		2	34.130	0.402	0.975	0.802	7.890
		3	61.870	0.081	0.180	0.573	4.411
		4	34.930	0.188	0.356	0.750	7.417
		5	39.200	0.118	0.376	0.595	4.509
	Level 3	1	50.000	-0.077	0.272	0.536	4.038
		2	62.670	-0.006	0.205	0.212	0.329
		3	18.670	0.759	1.076	0.929	8.131
		4	10.000	0.517	0.785	0.781	7.193
		5	70.400	0.311	0.678	0.702	7.289
	Level 4	1	15.730	0.497	0.769	0.972	7.966
		2	43.470	-0.015	0.478	0.462	1.998
		3	23.600	-0.028	0.485	0.694	4.984
		4	17.870	2.221	2.957	0.989	10.162
		5	18.000	-0.226	0.645	0.696	6.442